Managing Highway Bridges against Climate-Triggered Extreme Events in Cold Regions

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Abstract

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Highway bridges represent a significant investment by Governments at both Provincial and Federal levels and their importance is underscored by the fact that every citizen derives a benefit, directly or indirectly, from public transportation infrastructure. As with any engineering product, highway bridges must be well designed and robust to avoid any malfunction that could jeopardise the lives of people. Further, highway bridges deteriorate over time and need preservation intervention applied at suitable intervals over the bridge's service life. Determining the timing and order of implementation of preservation work among deficient bridges in a highway bridge inventory is an important function of bridge management.

The doctoral research reported in this thesis aimed to devise a method for the resilience/vulnerability rating of highway bridges against climate-triggered extreme events/ loads. The research also sought to devise a ranking technique for bridge projects' programming by pursuing a one-directional, non-iterative, method that could maximize the value function and significantly cut down the computer run time for the ranking analysis.

The research outcomes include a weighted-criteria method for the multi-criteria ranking, a practical tool for the resilience/vulnerability rating of highway bridges against extreme events such as deck flooding and abutment washout, and a method for determining the magnitude of climate-triggered extreme load (e.g. ice accretion, pier scour) that could potentially cause bridge failure.

The projects' ranking method developed in this research, including the development of a weighted criteria formulation, could potentially be adopted by bridge management systems in North America and elsewhere. Further, it is expected that the method will influence future development of multi-criteria ranking in bridge management and other fields. Similarly, the proposed new method for climate change resilience rating of highway bridges is a significant effort at translating the general scientific and engineering impacts' discussion of climate change into an engineering tool for the continuous management of bridges. Finally, it will be important for transportation agencies to determine beforehand what magnitude of climate-triggered extreme load would produce bridge distress and potential failure, and this thesis provides a solution to that problem.

Dedication

To

Professor Etim Moses Essien
Professor Ephraim Okon
Architect Idongesit Essien
Mr. G. C. Oniko
The memory of my father Obong Sandi Ikpong
My sister Arit Effiong Ekwere

who set me up for this great opportunity

Many thanks to

My wife Theresa Ikpong
My children Idongesit-Essien, Maeyen, and Idara

for their unflinching support

A big thank you to

My supervisor Dr Ashutosh Bagchi

for piloting this effort to success

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Yukon Department of Highways and Public Works

for sharing information on the bridges in that region

Managing Highway Bridges against Climate-Triggered Extreme Events in Cold Regions

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List of Abbreviations

Abbreviation	Name
A	Ice Accretion
AASHTO	American Association of State Highway and Transportation Officials
ACIA	Arctic Climate Impact Assessment
AHP	Analytic Hierarchy Process
ANP	Analytic Network Process
AW	Abutment Washout
BCI	Bridge Condition Index
BMS	Bridge Management System
BR	Bridge Resilience
BrM	AASHTOWare Bridge Management software
BSR	Bridge Sufficiency Rating
C	Consequence
CSA	Canadian Standards Association
CCPE	Canadian Council of Professional Engineers
CSIRO	Commonwealth Scientific and Industrial Research Organization
DAP	Dynamic Adaptive Planning
DM	Decision Making
DOT	Department of Transportation
EU	European Union
FHWA	Federal Highway Administration

FAHP	Fuzzy Analytic Hierarchy Process
FANP	Fuzzy Analytic Network Process
Ftg.	Footing
IIPC	Intergovernmental Panel on Climate Change
ISO	International Standards Organization
LL	Live Load
LOS	Level of Service
MINLP	Mixed-Integer Nonlinear Programming
MPO	Metropolitan Planning Organizations
MR&R	Maintenance, Rehabilitation, and Reconstruction
MAUT	Multi-Attribute Utility Theory
MCDA	Multi-Criteria Decision Analysis
MCDM	Multi-Criteria Decision Making
MORDM	Many-Objective Robust Decision Making
NAS	National Academy of Sciences
NBI	National Bridge Inventory
NCHRP	National Cooperative Highway Research Program
NP-hard	Non-deterministic Polynomial hard
NPV	Net Present Value
NRCAN	Natural Resources Canada
OBMS	Ontario Bridge Management System
OIS	Optimum Intervention Strategy

PIEVC	Public Infrastructure Engineering Vulnerability Committee
R	Rating, Resilience, Risk
RI	Resilience Indicator
R-Index	Ranking Index
TRB	Transportation Research Board
ULS	Ultimate Limit State
V	Vulnerability
W	Weight

Chapter 1

Introduction

1.1. Introduction

Highway bridge engineering practice encompasses bridge structural engineering, bridge construction, as well as bridge inventory maintenance and preservation management. Highway bridges need routine maintenance in addition to major preservation intervention implemented at suitably selected intervals over the service life of the bridge. Without routine maintenance, condition deterioration accelerates, costing much more to restore the bridge to an acceptable serviceable condition. At the same time, major preservation intervention is required over longer intervals in order to minimize the bridge`s total life cycle cost.

There is also a new factor to consider, namely, climate change impacts. The projected climate change impacts on transportation infrastructure in the Canadian North and Alaska in the last quarter of this century necessitate the development of new tools for assessing the projected climate change infrastructure vulnerabilities. Two types of climate-triggered demands on Northern transportation infrastructure will be studied. Demands such as abutment washout, deck flooding, and abutment permafrost instability have no bearing on the bridge's structural capacity and will be categorized as climate-triggered *extreme events*. On the other hand, demands such as extreme ice accretion and extreme hydrostatic forces on piers (extreme pier scour) will be categorized as climate-triggered *extreme loads*.

According to the Arctic Climate Impact Assessment (ACIA 2004), a moderate scenario of future climate warming would produce a sea level rise of 350 mm in the Canadian North. Over the past half century, the ACIA explains, winter temperature increase in the Alaska and North-Western Canada region has been in the range of 3-4°C, permafrost has warmed by up to 2°C in recent decades, the depth of the layer that thaws each year is increasing in many areas, and permafrost southern limit is projected to shift northward by several hundred kilometres this century.

The ACIA (2004) further notes the following. *"Thawing permafrost, which weakens coastal as well as interior lands, which in turn makes vulnerable the foundations for buildings and road infrastructure, is an important problem that needs to be addressed. More incidents of settlement and differential settlement of roadway, bridge, and building foundations will accompany the projected twin occurrences of increased permafrost temperature and the increased depth of the active layer. This will necessitate remedial measures for existing structures as well as for future projects that neglect to account for the warming trends. Stability of ground slopes will be compromised. If preventive measures are not taken to safeguard existing structures in permafrost regions, costly rebuilding should be expected. Furthermore, if new guidelines are not developed and adopted for future design and construction, the future could be very disruptive and expensive owing to ill-preparedness".*

The methods developed in this thesis for the study of climate-triggered extreme events and climate-triggered extreme loads consider the *scenarios* of sea level rise, permafrost warming, and increased precipitation projected for the Canadian North as cited above. These methods are tailored to the rating of highway bridges with respect to the extreme events and extreme loads, including determining the magnitude of climate-triggered extreme load that may cause the failure of a highway bridge, and to multi-criteria ranking of bridge projects for preservation intervention under budget constraint.

Finally, it should be noted that the analysis of climate change impacts on highway bridges as presented in this thesis are *scenario-based*, and it is not possible to quantify the probability of impact based on a limited set of scenarios. In order to calculate the probability of impact, the probability of occurrence of the extreme events and extreme loads need to be estimated. In addition, the uncertainty in estimating the parameters governing the capacity or resilience of a structure also needs to be accounted for. Such analysis is beyond the scope of the present study. In this case, scenario analysis indicates what the impacts and vulnerability rating would be if the assumed *scenario* materialised.

1.2 Motivation and Problem Statement

There is hardly any criterion more important in bridge management than load rating, but a bridge that has adequate resistance to truck live loads can still be vulnerable to climate-triggered extreme events such as abutment washout or abutment permafrost instability. Therefore, the climate change resilience rating research presented in this thesis sought to quantify *climate change impacts* in terms of engineering parameters so that remedial measures can be devised. These engineering parameters can be measurements of environmental and structural response parameters, cause and effect, input and output, capacity rating, failure impacts, and strength reserve. While the authors of current bridge management systems (BMSs) have noted the need for expanding the systems to include more functional aspects of bridge performance, to date no method has been proposed for climate change resilience rating of highway bridges. Clearly, there is need for a new procedure for extending the asset management scope for highway bridges to incorporate the resilience or vulnerability of a bridge against climate-triggered extreme events. Such a procedure/method should provide for *resilience indicators* to quantify the resilience of the various components of highway bridges against climate-triggered extreme events. The method should also provide for *capacity measures* that indicate how well a bridge is equipped to withstand the projected climatic effects. Further, the formulation of the method would require *weights* to be assigned to each resilience indicator so that, taken with a bridge's *rating* on each of the capacity measures, a single score, namely, the Bridge's *Resilience* rating, can be determined.

Further, it is also important to note that while a bridge may never experience a climate-triggered extreme event over its life cycle, no bridge can escape time-dependent deterioration. Over time, all bridges would experience deterioration of condition. Therefore, a bridge that is properly designed still needs to be inspected at designated intervals, maintained, and preserved over its entire service life. This means that maintenance and preservation management of all the bridges in a transportation agency's inventory is a very important function. If properly managed, the maximum possible length of service life per dollar of total life-cycle cost of the bridge can be achieved.

The timing of preservation actions over the life cycle of a bridge is what determines the scope and cost of such interventions, and it is what ultimately determines the failure or success in reaching the goal of maximum service life at minimum life cycle cost. This is where improved projects' selection and programming comes in. Bridge Management experts (Thompson et al. 2008, Ellis et al. 2008, Thompson et al, 2003, Markow 2008, Mach and Hartman 2008, and Hajdin 2008) are in agreement that more criteria should be considered in the optimization of bridge projects selection/programming. However, in the United States, for example, published literature indicates that bridge projects` selection is based on 2 criteria at the most. The present research effort sought to introduce a method that would take into account all the criteria that the transportation agency deems each important enough to govern the programming of a bridge project ahead of other bridge projects, and do so simultaneously and in a direct, non-iterative fashion.

Finally, if a bridge should be at risk of encountering a climate-triggered extreme loading, it would be desirable and important to know what magnitude of the extreme load would exhaust the bridge's strength reserve. Hence this research also sought to propose a method for calculating the magnitude of climate-triggered extreme load (pier scour, ice accretion, etc.) that would precipitate the collapse of a highway bridge.

1.3. Research Objectives

The present research has the following main objectives.

1. Devise a practical procedure for climate change resilience rating of highway bridges.
2. Develop a weighting method and a rating scheme for accomplishing the first objective.
3. Develop a method for determining the magnitude of climate-triggered extreme load that would cause the failure of a highway bridge.
4. Propose a simple and direct procedure for the multi-criteria ranking of bridge projects, which would be suitable for large bridge inventories while permitting the inclusion of new criteria such as climate-triggered extreme events vulnerability and climate-triggered extreme load resilience rating of highway bridges in cold regions.

5. Provide a critical comparison of the performance of the new ranking method's weight formulation with weights determined using the Analytic Hierarchy Process (AHP).

1.4. Organization of the Thesis

The thesis is divided into 8 chapters, including *Chapter 1 – Introduction*. Chapter 2 presents a review of available literature on the 3 main subjects covered in the thesis while Chapter 3 describes the research methodology and necessary tasks to achieve the objectives of the research, including data collection. Chapters 4, 5, 6, are devoted to the main topics of the research. *Climate change resilience rating of highway bridges* is developed in Chapter 4, Chapter 5 is reserved for the *determination of the magnitude of climate-triggered extreme load that would produce the collapse of a highway bridge,* while Chapter 6 deals with *multi-criteria ranking of bridge projects*. Chapter 7 presents a comparison of the performance of criteria weights calculated using the new approach introduced in this thesis against weights calculated using the *Analytic Hierarchy Process (AHP)*. Finally, Chapter 8 presents a *Summary* of the work undertaken within the research, the *Conclusions* reached, and the *Contribution* to knowledge made by the research.

A list of the publications derived from the research is included in the Appendix.

Chapter 2

Literature Review

2.1. Introduction

Having identified the objectives of the thesis, literature review was conducted to determine the state-of-the-art of the relevant topics, identify past contributions, and isolate the remaining research gaps. In the following, the findings from the study of available literature are presented, and then summarized at the end.

2.2 Multi-Criteria Optimization of Bridge Project's Selection and Programming

There have been frequent and considerable effort directed at the formulation of optimization and prioritization schemes but the proper construction of criteria weights remains a difficult problem. Past research work in this area are summarized below.

Stewart et al. (2013) explored the integration of multi-criteria decision analysis and scenario planning. Hamilton et al. (2013, 2015) discussed case studies in which scenario analysis was used to demonstrate the prioritization of investment actions under uncertain conditions such as urban growth, economy, market, regulation, ecology, climate, and innovation. Kasprzyk et al. (2009) explored the use of multi-objective optimization for water resource planning and for managing the risks of droughts as they affect water supply within a city. These studies did not yield methods that could be applied to the optimization of transportation infrastructure projects' selection.

Montibeller et al. (2006) aimed to integrate multi-criteria decision analysis with scenario planning for the purpose of ranking alternative strategies. The study found that a recurring problem is the difficulty that decision makers experience in establishing criteria weights and performance rating of the alternative strategies. The study also determined that using constant weights across all the alternative strategies presents shortcomings, and they recommended varying criteria weights from one strategy alternative to another (Montibeller et al. 2006). Joshi and Lambert (2007) pursued a methodology for the multi-objective combinatorial optimization of the selection of a few critically important projects out of many competing transportation improvement projects. The main aim of the work was to incorporate equity (fairness) in the spatial distribution of the selected projects across the geographical jurisdiction in addition to cost-benefit tradeoffs. These studies involved tradeoffs of selection criteria, and dealt with prioritization schemes as opposed to optimization techniques.

Alfares and Duffuaa (2009) proposed a methodology for calculating criteria weights for multi-criteria decision analysis. The weights were calculated as a function of the criteria rank and the total number of criteria. The methodology is built on the concept of relative importance of the selection criteria, which the authors describe as the cornerstone of multi-criteria decision making (MCDM). Criteria ranking is the primary information required for constructing the methodology, and the said ranking is elicited from decision makers (Alfares and Duffuaa 2009). It is further assumed that rank is inversely related to weight so that the top-ranked criterion has the largest weight (Alfares and Duffuaa 2009). Criteria weight remains constant across all strategy alternatives. At the extremes, where there are many criteria, the methodology described by Alfares and Duffuaa (2009) approaches a one-criterion prioritization technique in which a few top-ranked criteria dominate. With direct but subjective criteria ranking and constant weights, this effort, too, dealt with prioritization as opposed to optimization.

Keisler (2009) pursued a study of various approaches to determining weights for multi-criteria portfolio decision analysis. The study also evaluated the performance of the various approaches to weight determination by examining the value added to the prioritization ranking result. This was done by comparing each approach to a baseline case of random ordering of the alternative projects. Among the weight options used for the study were: equal weights, picking one attribute at a time on which basis to assign weights to competing alternatives, and weights based on the opinions of a single randomly selected stakeholder. Evidently, these are unsatisfactory methods to determine weights.

In another study, Wu et al. (2013) investigated scenario-based climate change risk analysis using GIS-based tools. The two climate-triggered extreme events considered were sea level rise and storm surges for the Hampton Region in the state of Virginia, United States. The analytic hierarchy process (AHP) was used for determining the weights assigned to the various influential factors. The risk value was calculated using an additive function and the criteria weights remained constant across the competing transportation objects (bridges, highways, airports, railroads, and ports). As will be shown in Chapter 7, there are significant shortcomings that come with the use of the AHP for determining criteria weights.

Ram and Montibeller (2013) investigated the combined use of scenario planning and multi-criteria decision analysis (MCDA) to evaluate alternative strategies. The formulation of weights is a variant of the familiar multi-attribute hierarchy process and therefore subjective and based on stakeholder or expert opinion. To determine weights, the stakeholder is asked to pick the criterion that they deemed the most important under a named scenario. A score of 100 is awarded to that criterion, and the other criteria are scored relative to the said top-ranked criterion, and the weights are then normalized. The foregone method for determining weights is obviously subjective.

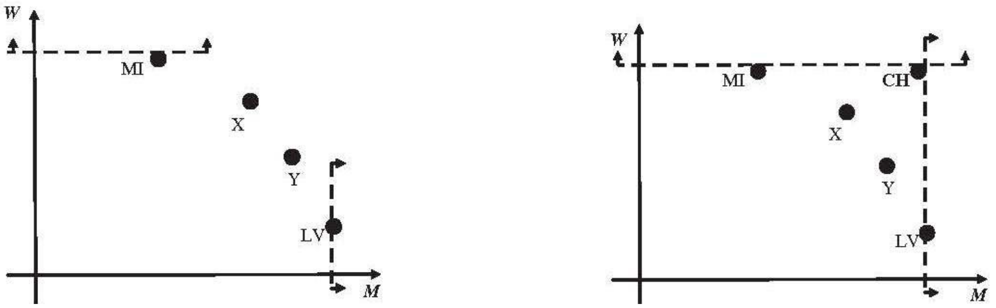
Espinet et al. (2015) proposed a method for constructing a decision support framework that could circumvent the uncertainty associated with future climate change projections. The method comprises 4 steps: quantification of costs and benefits of adaptation strategies, determining economic indicators for each strategy, comparing strategies across all future climate change scenarios, and evaluating regret and robustness of each strategy. The economic indicators step is where the costs of climate change vulnerability and the cost of the adaptation strategy to eliminate that vulnerability is calculated. Where an adaptation strategy is applied to reduce the vulnerability to zero, climate change risk is deemed totally eliminated. At the other extreme, where no adaptation strategy is applied to the infrastructure, the full level of risk applies. In general, some money will be spent to eliminate some of the risk (initial cost), and some additional money will need to be spent during the remaining life span of the infrastructure to eliminate the remaining risk (repair cost). The net present value (NPV) of the total cost is the sum of the NPV of the above two components, and this cost is the total life cycle cost of the adaptation strategy. For each infrastructure, the adaptation strategy with the lowest life cycle cost is selected.

It should be noted that for each adaptation strategy, there will be as many different life cycle costs as there are climate change scenarios. At this point, the scenario adjudged to be the most beneficial as the basis for adaptation design is selected. The relationship between the selected scenario and the scenario that may actually occur is tracked. Next, a payoff table is built where the rows are the scenarios that the strategy is designed for and the columns are the scenarios that actually occur. The study considered only the climate scenarios of temperature, precipitation, and flooding. The study does not name vulnerability indicators or capacity measures, does not consider highway bridge vulnerability, and does not contemplate optimization of projects selection that considers the traditional criteria together with the climate change criterion.

Zeleny (2011) presents extremely valuable information on optimization of decision making (DM) as follows. There is no decision making in the absence of tradeoffs (Zeleny 2011). In other words, there is no decision to be made. Following measurement and search, the answer to the problem becomes obvious. Further, there can be no tradeoffs along a single dimension (criterion) or in the presence of a prominent alternative (Zeleny 2011). For analysis involving a single criterion, measurement and search are sufficient. It follows that decision making can be defined as a "*function beyond measurement and search, aimed at managing, resolving or dissolving the conflict of trade-offs*" (Zeleny 2011).

Zeleny (2000) asserts that "*the existence of tradeoffs is a necessary and sufficient condition for decision making. Our task is to control, reduce or eliminate trade-offs from decision-making situations. Tradeoffs are not good and they are not necessary; they are neither preferred nor desirable; they are a testament to badly designed, inefficient and wasteful systems, the legacy of satisficing and the source of human discontent. Tradeoffs beg and challenge to be eliminated*."

In criticizing the formulation of prioritization/optimization problems, Zeleny (2010) again identified tradeoffs as the main culprit because optimization is impossible in the presence of tradeoffs. Further, problems have to be re-formulated to eliminate tradeoffs. Decision makers should not settle for problems as given (*a priori*) and, finally, to attain optimization, poorly configured (given) problems must be re-configured in order to enable optimization (Zeleny 2010).



(a) Conflict Resolution (b) Conflict Dissolution

Fig. 2-1 Tradeoffs Prevent Optimization (Zeleny 2011)

As an example, Zeleny (2010) presented a case where a decision was to be made on which of 4 alternatives should be selected. When presented with the four options MI, X, Y, and LV (Fig. 2-1), the decision maker ended up with 2 alternatives, one of which satisfied Part 1 of 2 of the selection criteria while the other alternative satisfied Part 2 of 2 of the criteria. Zeleny (2010) argued that it should not be accepted that there are only 4 alternatives. Why not re-formulate the problem (devise a radically new model, reconstitute the criteria, etc.) to include other options such as CH (Fig. 2-1b), which is far North enough and far East enough to meet both parts 1 and 2 of the selection criteria? Fig. 2-1a depicts conflict *resolution* involving tradeoffs of either Part 1 or Part 2 of the selection criteria. Fig. 2-1b, on the other hand, depicts conflict *dissolution* in which both parts of the selection criteria are satisfied. Here, the lesson is: eliminate tradeoffs and you achieve *optimization* of the selection problem (all criteria satisfied). Alternatively, accept tradeoffs and all you achieve is *prioritization* in which something is given up in order to gain something else.

Kasprzyk et al. (2013) proposed a many-objective robust decision making (MORDM) methodology, which generates alternatives for complex planning problems and, thereby, isolate the key tradeoffs among the planning objectives. The method is said to be geared towards the identification of the most important vulnerabilities in the studied system, but it does not provide for the optimization of projects' selection in which tradeoffs are a redundant concept.

Adey et al. (2012) proposed a list of criteria for inclusion in the evaluation of the optimum intervention strategy (OIS) for a highway segment comprising multiple objects (for example, a bridge and the two road segments leading to the bridge). The finely delineated criteria are classified into the following four hierarchies: Owner, Users, Directly Affected Public, and Indirectly Affected Public. The idea of *hierarchy* is not to rank the criteria on the basis of their level of importance but to identify each criterion and to take it into consideration in evaluating the various intervention strategies. Notwithstanding the above, each stakeholder is identified as either a first-level or a second-level stakeholder, where first-level stakeholders are defined as stakeholders whose net positive impacts should be maximized and second-level stakeholders are defined as those whose impacts derive from the outcome of the maximisation of the net impacts of the first-level stakeholders.

The available strategies comprise different combinations of the three objects (two road segments and the bridge that connects them) to be refurbished or rebuilt at any one time until all three objects have been restored to a satisfactory *level of service* (LOS). The evaluation of the various strategies is performed using mixed-integer nonlinear programming (MINLP). The method seems suited to road construction projects in which the road segments requiring intervention are physically connected, and without physical separation. It does not seem to contemplate competition among all the projects slated for intervention within an entire jurisdiction, with projects located hundreds of kilometres apart. Further, the method appears useful for determining, numerically, the advantage in undertaking intervention in one piece (i.e. all 3 of 3 objects), at the same location in a road network, versus doing 1 of 3 at a time or 2 of 3 at a time, and which 2 of 3, when? The method could possibly be used to select an optimum intervention strategy (optimum project) for a bridge, namely, select the type and extent of work to be executed on a specified bridge among other alternative types and extents of work. A pool of similarly selected optimum projects for every bridge identified for intervention jurisdiction-wide could then be programmed at the network level, under budget constraint, using the multi-criteria ranking method proposed in this thesis.

Also, to use this method, the *Do-Nothing* project alternative (i.e. the *Do-Nothing* intervention strategy) would have to be included at the network level for each bridge for which an optimum project has been selected. That's how the Agency Benefits criterion (utility criterion) is accounted for, namely, the amount of money saved by the Agency in undertaking the intervention now compared to doing-nothing now, postponing the intervention for, say, 10 years so that further deterioration of the bridge occurs, which makes the intervention more costly.

Further, under budget constraint, network-level optimization, in contrast with project-level selection of OIS, features an increase in cost for a delayed project for a specified bridge by the time the intervention is implemented in the future but, simultaneously, there is an intervention that is implemented on another bridge during the current programming period. So, while there will be negative impacts emanating from the deferred intervention on the one bridge, there would be positive impacts elsewhere in the network that offsets the said negative impacts. It would appear that such a phenomenon is non-existent at the project-level OIS analysis as contemplated by Adey et al. (2012). Finally, all positive impacts would have to be expressed as a ratio of *Impact per Dollar* spent by the transportation agency prior to proceeding with multi-criteria ranking as proposed in this doctoral thesis.

Essahli and Madanat (2012) proposed a procedure for the prioritization of bridge deck maintenance, rehabilitation, and reconstruction (MRR) with the objective of minimizing the probability of failure of the bridge network under budget constraint. On the basis of the jurisdiction map, the procedure is said to be capable of identifying the bridge(s) that serve as the vital link in the network, which must be kept serviceable at all times during the planning horizon of 30 years. The procedure is said to be also capable of modeling the tradeoffs between the relative location of each bridge on the network, rate of deck deterioration, and deck intervention cost, and to optimize the selection of deck intervention projects with respect to those 3 variables. However, the model prioritizes only on the basis of agency cost, to the exclusion of other recognized prioritization criteria such as utility (agency benefits), user cost, and vulnerability to extreme events. Obviously, the method was tailored to prioritization rather than optimization.

Kim et al. (2013) proposed an optimization formulation for maximizing the expected service life while minimizing the total life-cycle cost of any type of structures that are subject to time-dependent deterioration, including highway bridges, ships, buildings, and aircrafts. In other words, the model aims to maximize the ratio of bridge condition improvement (bridge performance) to the cost of intervention (cost of inspections and rehabilitation) implemented for the purpose of extending the service life of the structure. While the method, as proposed, covers only structures which deterioration, loss of serviceability, or outright collapse are time-dependent, the authors suggest that it could be extended to account for the risk of failure or reduced level of service due to extreme events. In comparison, it will be shown later that the method proposed in this thesis does account for time-dependent deterioration of the condition of highway bridges as well as climate-triggered extreme events and climate-triggered extreme loads.

Zhu and Frangopol (2013) noted that highway bridges could reach failure via time-dependent deterioration and mechanical loads, or via sudden collapse caused by an extreme event/loading. To account for both of these sources, Zhu and Frangopol (2013) proposed a method for assessing the probability of such failures occurring as well as examining the effects of such failures on the economic and social interests of road users and the public at large. Noting that most previous assessments of risk were qualitative and therefore of limited value, the authors assert that quantitative assessments are required in order to obtain clear and accurate results. According to Zhu and Frangopol (2013), the three components of quantitative risk assessment are: hazard analysis, vulnerability analysis, and consequences analysis. As will be shown later, these three components match the three steps outlined in *Chapter 3 Research Methodology and Data Collection* for climate change resilience rating of highway bridges.

Various researchers at Concordia University in Montreal have studied different aspects of highway bridge preservation, including condition assessment of concrete bridge decks (Dinh 2014), deterioration models for bridge decks (Ghodoosipoor 2013), and condition assessment of concrete bridges (Yaghi 2014). These studies are useful for the bridge performance rating of bridges, after which the ranking of bridge projects' selection, as developed in this thesis, can be pursued.

El Chanati et al. (2015) determined criteria weights for the multi-criteria performance rating of water pipelines by comparing the reliability of four methods, namely, Analytic Hierarchy Process (AHP), fuzzy AHP (FAHP), Analytic Network Process (ANP), and fuzzy ANP (FANP). The weights were ultimately based on the FANP because it proved to be the most accurate. The three weights considered in the study were determined to be: physical, environmental, and operational. While this approach might have improved the estimate of weights, it is still a subjective method, the value function is not maximized, and projects' selection is not optimized.

Abu Dabous and Alkass (2011) developed a methodology for projects selection under budget constraint, including evaluation and ranking of available rehabilitation strategies for each project. The methodology is said to integrate the *Analytic Hierarchy Process (AHP)* and the *Multi-Attribute Utility Theory (MAUT)* to extract experts' knowledge and judgments while incorporating quantitative and qualitative criteria in decision making.

The advantages accruing from the AHP are cited as simplicity and the ability to handle complex decision-making problems. For its part, the MAUT provides the ability to include in the analysis multiple and conflicting criteria (Abu Dabous and Alkass 2011). The criteria considered included agency cost, user cost, bridge safety, bridge deck useful life, and environmental impacts. The study was limited to *bridge deck* maintenance, repair, and replace (MR&R) projects. As with other instances of multi-criteria prioritization and ranking studies found in literature, the procedure is iterative.

The authors themselves delivered the following assessment of their method (Abu Dabous and Alkass 2011). In a case study involving 3 top-ranked bridge projects demonstrated in the study, 27 work programs (27 MR&R strategy combinations) were available for evaluation based on 3 projects and 3 possible strategies. At that rate, 20 projects would attract 3,486,784,401 [3.5 billion] work programs. The authors cited this as a limitation of their methodology, and they recommended further research work aimed at eliminating this drawback. The present research effort would be helpful in mitigating such problems.

Finally, there are but a few instances in literature in which the optimization techniques used widely by transportation agencies have been published, and these are discussed below.

Pontis, USA

The approach to optimization in *Pontis* (now called the AASHTOWare Bridge Management software or **BrM**) can be summarized as follows. The formulation of a solution for a multi-criteria (multi-dimensional) optimization of bridge projects' selection is considered to be a *Non-deterministic Polynomial* hard (NP-hard) problem, for which there is yet no exact solution (Thompson et al. 2008). According to Thompson et al. (2008), the problem has received considerable attention from operations research experts, with some level of success for small to medium size problems. However, the required formulation is intractable for large-size problems such as inventories comprising over 10,000 bridges. The problem is a special case of integer programming problems. Because no known deterministic polynomial algorithm exists, the optimal solution grows exponentially as the size of the problem grows.

Thompson et al. (2008) estimate that it would take 3 days to process 12,000 bridges using an *optimization algorithm*, 2.5 hours using a *polynomial algorithm*, and 13 minutes using *simple sorting* of the type recommended by Thompson et al. (2008), which is described below. In the case of the 50,000-bridge Texas DOT, the processing times would be 45 days, 1.7 days, and 31 minutes for optimization algorithm, polynomial algorithm, and simple sorting, respectively.

To overcome such difficulty, AASHTO's bridge management software ***BrM*** uses a *simple sorting* method following the National Cooperative Highway Research Program's *NCHRP*

Report 590 (Thompson et al. 2008), which recommended a multiple-criteria optimization methodology based on the incremental utility/cost heuristic. In this method, a list of project alternatives is created for each bridge that requires intervention. A larger list is then created comprising multiple alternatives per bridge. This list is the final output of the project-level analysis. Optimization is undertaken at the network level, and the first step is to create 2 lists: List "A" contains performance/cost ratio for each project while List "B" contains utility/cost ratio for each project. Both lists are sorted in descending order. The optimization algorithm first removes all the Do-Nothing alternatives from List "A"; then accumulates the remaining projects of List A into another list, List "C", in the order of their performance/cost ratios, one at a time with the highest ratio first, each time accumulating the cost of each project selected so as to have a cumulative total after each project is added into the list.

This continues for as long as the budget is not exceeded. If the budget is exhausted, the algorithm at that point evaluates the network *bridge condition index* (BCI). If the Network BCI target has been met, the process stops. Otherwise, the lowest project from List "A" is removed from List "C" and returned to List "A", and the project with the highest ratio in List "B" is selected and added into List "C". A revised Network BCI and a revised cumulative total cost are calculated. Both the performance and budget criteria are checked; and this continues until sufficient "bottom" projects in List "C" are replaced by "top" projects from List "B" such that the performance target is met and the budget is not exceeded if at all possible.

The final contents of List "C" are adjudged to be the projects which implementation will yield the highest network performance for the available budget while also possibly attracting the most benefits at the minimum long-term cost. With that, the optimization computation cycle comes to an end. On the other hand, if there is sufficient budget to meet the set performance target, then, utility is ignored and the projects are programmed for implementation solely based on the performance criterion, which then amounts to a one-criterion "optimization". The above description is demonstrated in Table 2-1 and further explained in the following.

For 10 bridge projects to be optimized, the ranking based on the performance criterion is as shown in Table 2-1 (Columns 2 and 3), which also shows the ranking on the utility criterion

(Columns 5 and 6). The list of projects ranked based on the performance criterion, which also satisfies the budget constraint is called List "C" in the ***BrM*** method, and that list is shown in Column 7 of Table 2-1. List "C" (Column 7 of Table 2-1) contains 8 projects in the order of priority, with top priority going to Bridge #10 and the least priority is accorded to Bridge #8.

Table 2-1 Optimization using the ***BrM*** Method

Bridge ID 1	Performance/ Cost (Max 100%) 2	Perf/Cost Ranking 3	**Bridge ID** 4	Utility/Cost (Max 100%) 5	Utility/Cost Ranking 6	***BrM*** List "C" Performance Only 7	***BrM*** List "C" Performance + Utility 8
#10	100.0	1	#5	100.0	1	Bridge #10	Bridge #10
#9	80.0	2	#7	89.6	2	Bridge #9	Bridge #9
#6	74.4	3	#6	80.0	3	Bridge #6	Bridge #6
#3	73.1	4	#2	77.4	4	Bridge #3	~~*Bridge #3*~~
#4	73.0	5	#9	75.7	5	Bridge #4	~~*Bridge #4*~~
#5	27.4	6	#3	72.2	6	Bridge #5	Bridge #5
#2	27.1	7	#4	67.0	7	Bridge #2	~~*Bridge #2*~~
#8	22.3	8	#1	65.0	8	Bridge #8	Bridge #7
#1	19.3	9	#10	63.5	9		
#7	6.2	10	#8	60.0	10		
Total Cost						$11,782 m	$12,188 m

The two projects that do not make the list are Bridge #1 and Bridge #7, and they are excluded because their inclusion would violate the budget constraint criterion. The total cost of these 8 projects is $11,782,000, which is a little below the available budget of $12,542,900. Since the performance target of 80.3% is not met (it takes $25,085,000 to achieve 80.3% performance rating), next, ***BrM*** substitutes the bottom projects in List "C" with the top projects of List "B" (the utility List). The final list and order of implementation of projects is shown in Column 8 of Table 2-1, as follows: Bridges #10, #9, #6, #5, and #7. This is deemed to be the optimized order.

One of the shortcomings of the ***BrM*** method is that, in addition to being iterative, the method is limited to two criteria and is not capable of handling 4-criteria optimization.

KUBA, Switzerland

The Swiss Federal Roads Authority manages a total of about 3,500 bridges on the national roads network using a bridge management system called KUBA (Hajdin 2008). The overall philosophy adopted by the Roads Authority is the universally accepted one, namely, that the goal should be an optimum balance between the cost and benefits of the national bridge infrastructure. In KUBA, optimization at the program level becomes necessary only if there is insufficient budget to undertake all the projects that are selected for each bridge structure that needs intervention (e.g. preservation or improvement). System-wide, the candidate projects representing all the bridges that need intervention have already been selected, one per bridge, at the project-level analysis stage, based on the minimum long-term cost criterion. Where there is insufficient funding to undertake all the selected projects in a given programming period, the cost-benefit criterion is used to optimize the projects' selection such that the greatest benefit is derived from the fixed budget outlay. With that, the projects' selection is deemed optimized.

2.3 Analytic Hierarchy Process (AHP) for Criteria Weights

The Analytic Hierarchy Process (AHP) was first proposed by Saaty in 1980 (Saaty and Vargas 2001) to provide a means for converting criteria ranking into criteria weights. In this method, criteria ranking is obtained via a pair-wise comparison of the relative-importance of all the criteria selected for a specified problem, two criteria at a time. Vashist and Dey (2016) have cited the AHP as a multi-criteria decision making tool that is based on the three principles of decomposition, comparative judgment, and synthesis of priorities. They further note that to use AHP, a hierarchy has to be established, comprising a goal, criteria, and alternatives. Next, two types of pair-wise comparisons have to be made: pair-wise comparisons between criteria that illuminate the priorities of the criteria with respect to the goal, and pair-wise comparisons between alternatives with respect to the criteria, which show the relative merits of the alternatives.

Scoring of the criteria is based on a scale of odd numbers in the range of 1 to 9 as shown in Table 2-2.

Table 2-2 AHP Pair-wise Comparison Schedule (Vashist and Dey 2016)

Level of Importance	Definition	Remarks
1	Equally preferred	Two factors contribute equally to the objective.
3	Moderately preferred	Experience and judgment slightly favor one over the other
5	Strongly preferred	Experience and judgment strongly favor one over the other
7	Very strongly preferred	Experience and judgment very strongly favor one over the other. Its importance is demonstrated in practice.
9	Extremely preferred	The evidence favoring one over the other is of the highest possible validity.

As an example of the interpretation of the judgments rendered by an expert in rating of the criteria, a rating (level of importance, Table 2-2) of 5 awarded to Criterion *A* relative to Criterion *B* implies that Criterion *B* must be rated $^1/_5$ based on the reciprocal axiom. The criteria rating are then used to establish the criteria weights by synthesis. Finally, the criteria weights are applied to the alternatives' rating to obtain the final achievements and priority ranking of each alternative.

2.4 Vulnerability of Highway Bridges to Climate-Triggered Extreme Events

The Federal Highway Administration (2011a) defines risk as "*the potential for an unwanted outcome resulting from an event, which is determined by the product of: (a) the likelihood of the impact, and (b) the consequence of the impact*". Similarly, ISO (2009) defines risk as the effect of uncertainty on objectives, often expressed in terms of a combination of the consequences of an event (including changes in circumstances) and the associated likelihood. Further, ISO (2009) defines vulnerability as the intrinsic properties of something resulting in susceptibility to a risk source that can lead to an event with a consequence. In this connection, a highway is considered to have adaptive capacity if it has detour/alternate/redundant routes (FHWA 2012). These definitions underline the approach taken in this thesis for the climate change vulnerability rating of highway bridges.

2.4.1 The Arctic Climate Impact Assessment

The research reported in this thesis was inspired by the findings of the 2004 Arctic Climate Impact Assessment, which is described below.

The *Arctic Climate Impact Assessment* (ACIA 2004) is one of the most comprehensive climate change studies ever undertaken. The study relied on climate historical data dating back to over 50 years ago as well as future climate simulations and climate models for the world and the northern Arctic region, where the highway bridges reported in this thesis are located.

The findings of the study (ACIA 2004) can be summarized as follows, for the period ending in 2100.

- Projected impacts are based on observed data and a moderate scenario of future warming, not a worst-case scenario.
- The assessed impacts apply only to the present century; impacts beyond this century were not within the scope of the study.
- Over the past few decades, the Arctic region has seen almost double the rate of temperature increase experienced by the rest of the world. This rising temperature has translated into widespread melting of glaciers and sea ice as well as rising permafrost temperatures.
- Over the past half century, winter temperature increase in the Alaska and North-Western Canada region has been in the range of 3-4°C.
- Permafrost has warmed by up to 2°C in recent decades, and the depth of the layer that thaws each year is increasing in many areas. Permafrost southern limit is projected to shift northward by several hundred kilometres this century.

- Glaciers throughout the Arctic are melting. In particular, the glacial melt in Alaska is so huge that it represents about 50% of the world's glacial melt. It also represents the largest melting-glacier contribution to rising sea level yet measured.
- Global and Arctic sea level has risen 100 mm to 200 mm over the 50 years dating back from 2004. At that rate, it is expected that by the 2070s, a sea level rise would be in the order of 250 mm to 500 mm, or an average of 375 mm (rounded to 350 mm).
- And what is yet to come? Temperature increase of 3–5°C over the land areas and up to 7°C over the oceans is projected. Winter temperatures are projected to rise significantly more, in the order of 4–7°C over the land areas and 7–10°C over the oceans.
- Further, the temperature increase is projected to be much greater in the Arctic than in the world as a whole.
- Global warming will result in increased evaporation and a consequent increase in precipitation. This is already happening. Over the Arctic region, a 20% increase is projected by the end of the century, with most of the increase manifesting as rain.

Why is this important? The following points are quoted from the ACIA (2004) to highlight the importance of global warming to the state of infrastructure.

- *"Thawing permafrost, which weakens coastal as well as interior lands, which in turn makes vulnerable the foundations for buildings and road infrastructure, is an important problem that needs to be addressed. More incidents of settlement and differential settlement of roadway, bridge, and building foundations will accompany the projected twin occurrences of increased permafrost temperature and the increased depth of the active layer. This will necessitate remedial measures for existing structures as well as for future projects that neglect to account for the warming trends."*
- *"Stability of ground slopes will be compromised.*"
- *"Research on the impacts of warming on infrastructure indicates that even small increases in air temperature substantially affect building stability, and that the safety of building foundations decreases sharply with increasing temperature. This effect can result in a significant decrease in the lifetime of structures as well as the potential failure of structures.*"

- *"If preventive measures are not taken to safeguard existing structures in permafrost regions, costly rebuilding should be expected."*

Furthermore, if new guidelines are not developed and adopted for future design and construction, the future could be very disruptive and expensive owing to ill-preparedness."

2.4.2 Studies of Climate Change Impacts on Infrastructure

Today, many governments in the developed world are taking steps to ensure that the impacts of climate change on transportation infrastructure are studied and documented (Erath et al. 2009, Moreno and Becken 2009, North Jersey Transportation Planning Authority 2011). For example, Report FHWA-HEP-12-010 (FHWA 2011b) aimed to provide guidance on the use of climate information when performing climate change vulnerability assessment of transportation infrastructure in the United States of America. In the United States, the Department of Homeland Security has an Office of Infrastructure Protection, which manages the National Infrastructure Protection Plan (Samford 2013).

Between 2011 and 2012, the Federal Highway Administration (FHWA) convened three workshops aimed at developing detailed approaches to climate change vulnerability assessment and adaptation for adoption by State Departments of Transportation (DOTs) and Metropolitan Planning Organizations (MPOs). The outcome of these workshops included a recommendation that each state DOT should specify which models, data, scenarios, and time frames DOTs and MPOs should use in adaptation planning (FHWA 2009). Another recommendation pertained to design standards, which should be re-evaluated and updated to account for climate change patterns.

Other climate change projection efforts in the United States include work by Karl et al. (2009), which warned that "*there will be a greater probability of infrastructure failures such as highway and railway bridge decks being displaced and railroad tracks being washed away"*. Citing Hurricane Katrina as one of the most destructive and expensive extreme climate event in the history of the United States, Karl et al. (2009) estimate the total recovery cost for bridges, roads, and utilities at $15 billion to $18 billion, including debris removal.

Ayyub and Kearney (2012) estimated that global sea level rise in the 21st century could be as high as 19.6 ft (5.9 metres), with melting of polar ice the chief contributor. Further, the increase in sea level rise could be as much as 2 to 3 times the increase that occurred in the 20th century, which itself saw the highest increase in 1,000 years. For context, Bloetscher et al. (2014) estimated 1.0 metres sea level rise for the state of Florida by the year 2100. The Union of Concerned Scientists (2009) have noted that the extreme flood in 1993 in the United States mid-West caused the damage and collapse of 9 highway bridges, and they asked how much more damage could be expected in 2093 (100 years from the 1993 mid-Western floods) if counter-measures are not taken in the coming decades.

Karvetski et al. (2011a) studied the prioritization of infrastructure upgrades in the presence of climate change extreme event scenarios. The scenarios considered included sea-level rise, increased frequency of forest fires, and permafrost melting. The paper states that "*Many independent sources have established that the effects of climate change are occurring sooner in arctic areas (Reiss, 2010; Wendler and Shulski, 2009; Larsen et al., 2008). Alaskan communities have already witnessed erosion and other changes in environment that have led to significant damage and threats to infrastructure, human health and safety, and economic opportunities.*"

Similar to many other climate change studies in the United States, Ayyub (2014) examined the climate change risk profile for the Washington DC geographic region as opposed to analysing specific infrastructure forming a part of an inventory. Nevertheless, the approach vindicates the cardinal elements of the methods proposed in this thesis: hazard likelihood assessment, scenario identification, consequence and criticality assessment using inventories of assets, and benefit-cost analysis. Further, the study (Ayyub 2014) investigated the single scenario-type sea level rise (SLR), to the exclusion of such scenarios as melting permafrost, ice accretion, pier scour, etc.

McLaughlin et al. (2011) studied the climate change vulnerability of the Port Authority of New York and New Jersey. The methodology comprised the following steps: definition of climate change variables and projections, development of asset inventories, vulnerability assessment, risk analysis, prioritization of assets and development of adaptation strategies. These more or less are in alignment with the methodology used for this thesis.

Oswald and McNeil (2013a) described a spreadsheet-based methodology for assessing climate change vulnerability of transportation infrastructure, mitigation, adaptation measures, and projects prioritization. However, the demonstration of the method is opaque as no infrastructure assets are isolated and no data analysis is presented.

Many other climate change studies deal with issues other than infrastructure vulnerability. For example, FHWA (2008a) deals only with greenhouse emissions by the various transportation modes. However, the report does note that a consideration of infrastructure impacts has not yet taken off because transportation agencies expect that it will be a couple more decades at least before those impacts materialize. Along the same lines, Metz et al. (2007) deals mostly with greenhouse gas emissions, with great emphasis on the meteorology of climate change, emissions as a function of the transportation mode, research and development in bio-fuels, truck weight reduction, etc. Mitigation of adverse consequences for transportation infrastructure or their vulnerability rating is not discussed. There is also the European Commission (2013a) Report, which doesn’t discuss climate change impacts on infrastructure or their rating on climate change vulnerability. But the European Climate Adaptation Platform (European Commission 2013b) does require that new infrastructure be climate-change-proofed so that their performance against future projected climate change impacts is enhanced.

There are also studies that, while not addressing or proposing methods for climate change vulnerability rating of transportation infrastructure, have documented the performance or efforts by transportation agencies in preparing for the projected future climate change impacts. For example, Oswald and McNeil (2013b) surveyed 18 Metropolitan Planning Organizations in the United States on their climate change adaptation practices, and they highlighted budget and regulatory restrictions as the major impediments to adaptation.

Beyond North America, climate change research is also being undertaken in Europe and elsewhere around the globe. In addition to the European Union (EU) climate change initiatives, Holland, Denmark, Germany, and Norway have a joint research effort to develop a preliminary risk assessment method aimed at identifying the most vulnerable locations in the roads network, assessing the probability of extreme climate events and their consequences, and outlining options for adaptation actions (FHWA 2015).

The United Nations has also played a leading role in climate change scientific research. The objective of the Intergovernmental Panel on Climate Change (IIPC) 4th Assessment Report (United Nations 2007) was to assess the scientific, technical and socioeconomic information on climate change, its consequences, and strategies for adaptation and mitigation. The report emphasizes projections for future temperature and precipitation increases, sea level rise, and effects on ecosystems and human communities, but it is not concerned with the rating of infrastructure on climate change vulnerability.

Similarly, IIPC's 5th Assessment Report (Field et al. 2014) describes the level of confidence in the projection for various key risks associated with climate change, the potential for adaptation, and the impacts on natural ecosystems, human livelihood and development, transportation and road infrastructure, among others. However, similar to the 4th Assessment Report, the 5th Assessment Report has nothing on climate change vulnerability rating of highway bridges or transportation infrastructure.

Of immediate relevance to this thesis is the climate change vulnerability rating of transportation infrastructure, and research work in this area are noted in this and the following paragraphs. In Canada, Seto et al. (2012) studied the climate change vulnerability of a highway segment constructed on permafrost in the Northwest Territories of Canada. The study identified the degradation of ice-rich permafrost as the cause of embankment deformations. Further, the study concluded that although the road embankment stability was insensitive to climate change, climate change would likely increase repair and maintenance effort if safe driving conditions are to be maintained (Seto et al. 2012).

Linkov et al. (2014) assert that although the number of climatic extremes may intensify or become more frequent, their impacts on society's infrastructure are not in any way quantified. The paper suggests that effective management of the risk for infrastructure posed by climate change should be approached based on the following four steps:

1. Develop specific methods to define and measure resilience
2. New modeling and simulation techniques
3. Development of resilience engineering
4. Approaches for communicating with stakeholders

In this connection, it should be noted that the National Academy of Sciences (NAS) defines resilience, thus, "*the ability to prepare and plan for, absorb, recover from, and more successfully adapt to adverse events*" (Linkov et al. 2014). Risk analysis, on the other hand, is defined by the NAS as "the quantification of the probability that the system will reach the lowest point of the critical functionality profile". Næss (2006) advocate viewing vulnerability assessment as a process and not a product, and urge complementary approaches that capture different aspects of vulnerability. In the case of highway bridges, climate-triggered extreme events and climate-triggered extreme loads, as proposed in this thesis, are important but new aspects that have to be accounted for.

The Federal Highway Administration (2012a) recommends that the objectives of a Climate Change and Extreme Weather Vulnerability Assessment Framework should include the generation of metrics to be incorporated into asset management, metrics to be integrated into emergency and risk management, and metrics on which to base project prioritization. The present doctoral research meets all 3 objectives.

Wall et al. (2015) proposed the use of dynamic adaptive planning (DAP) in climate change infrastructure adaptation plans to enhance flexibility and continuous adaptation throughout implementation. The method is proposed as a complementary next step to current vulnerability- or risk-based approaches to prioritization in transportation infrastructure management. The method is concerned with making modification to plans as they are implemented. So, it runs on a parallel track to the methods proposed in this thesis.

Karvetski et al. (2011b) proposed a methodology for multi-criteria decision analysis for prioritizing protective actions on coastal infrastructure to withstand various future climate change scenarios. Various magnitudes of sea level rise are selected as the scenarios while the protective engineering actions are the *project alternatives* to be prioritized, including revetments, sea walls, beach nourishment, and dune nourishment. The demonstration of the method does not account for the cost of the project alternatives or economic constraints because the methodology is intended to complement the cost and economic analysis. On the contrary, the present doctoral research is devoted to integrating the economic analysis of performance/cost and utility/cost with the climate change vulnerability rating of highway bridges.

Lambert et al. (2013a, 2013b) cite examples of prioritization schemes available in literature for evaluation of highway vulnerability, or qualitative vulnerability assessment of critical infrastructure sites, or assessment of transportation network vulnerability including a model for calculating failure consequence. They, however, add that none of the work to date has attempted to include the effects of climate change in transportation asset management. Therefore, Lambert et al. (2013b) have proposed a framework for prioritization in transportation asset management that takes into account potential climate change impacts. The method is called a *scenario-based multi-criteria decision analysis framework*. Its strength lies in the combination of the technique of multi-criteria decision analysis with scenario-based conditions, whereby the scenarios replace forecasts or probabilities. Within this premise, the need for accuracy of forecasts or calculated probabilities is eliminated, and scenarios simply describe what the outcome would be if the scenario were to materialize.

To summarize, Lambert et al. (2013b) do propose a multi-criteria prioritization method in which all the criteria are evaluated simultaneously and summed up to obtain a single score (maximum 100%) for the rating of assets or for the ranking of competing projects. However, Lambert et al. (2013b) does not provide for an objective method or any method at all for determining Criteria

Weights nor does it provide an objectively determined Rating Guide for the rating of highway bridges against climate change impacts.

In Europe, climate change projections pose similar problems. Leviäkangas et al. (2011) determined that road and highways are the most vulnerable to climate change impacts of all modes of transportation. In the U.K., where wetter winters and hotter summers are projected for the 2050s, the potential modes of roads failure are expected to include the social concept of a failed journey, road rutting, rail buckling, and earthwork failures (Wilks 2010).

At a global scale, Hirsch and Kuntsman (2014) undertook an overview of climate change risk management approaches in the United States, Europe, and New Zealand. Their findings show that the approaches taken in these regions represent a slight variation from a basic risk management method. In all cases, it is expected that a risk assessment would be required to be performed following the vulnerability analysis except that in the United States the risk assessment component is optional. In comparison, the method proposed in this thesis includes a risk assessment component in addition to the basic vulnerability analysis.

In Japan, the Government recently published a guideline for climate change adaptation (Ministry of Environment Japan 2015). Earlier, the Government of Japan (2009) issued a report entitled *Climate Change and its Impacts in Japan*, which discussed climate change and its consequences from the perspectives of the natural ecosystems, changes in precipitation and temperature regimes, changes in the Pacific Ocean temperature, climate change projections for the future, etc. However, the report did not include a study of the impacts on infrastructure or the vulnerability of infrastructure to climate change. Even so, Wise Adaptation to Climate Change (Committee on Climate Change Impacts and Adaptation Research 2008) prescribes the steps for climate change adaptation in Japan, which are similar to the steps used for the vulnerability rating of highway bridges in this thesis: ascertaining impact mechanisms, deciding on the important impact events to be watched, formulating methods for predicting impacts, delineating indicators and methods for assessing impacts, and devising methods for assessing vulnerability. However, no methods are presented for the vulnerability rating of highway bridges, nor are methods presented for the ranking of (bridge) projects' in which climate change vulnerability is a criterion.

In Australia, CSIRO (2007) examined the potential impacts of climate change on Victoria City's infrastructure and sought to identify the categories of infrastructure that would be most vulnerable. The main outcome of the risk assessment methodology in the CSIRO (2007) study is a *climate change exposure and infrastructure sensitivity matrix*. However, the study does not include a methodology for the continuous management of infrastructure assets via the climate change vulnerability rating of individual assets within an inventory or jurisdiction.

2.4.3 Public Infrastructure Engineering Vulnerability Committee (PIEVC)

In Canada, the most significant effort to develop a method for the management of the impacts of climate change on engineering infrastructure was undertaken and published in 2008 by the Canadian Council of Professional Engineers (CCPE) as a joint initiative with the Department of Natural Resources Canada (NRCAN). It details a protocol meant to serve as a blueprint on how to approach the assessment of the vulnerability or resilience of engineering infrastructure in Canada against the impacts of global climate change.

The steps for undertaking a vulnerability assessment using the PIEVC protocol are as follows (PIEVC 2008):

.1 Project Definition, in which the infrastructure is identified by its utility/function, its geographic location, its age, as well as the historic climate of its location.

.2 Data Gathering and Sufficiency, in which the infrastructure is isolated into its component parts (pier footing, pier shaft, steel girders, concrete deck, etc.), and the projected climate change events are specified (ice force on piers, freeze/thaw cycles, snow on deck surface – intensity/frequency, extreme wind storm, flooding of the river being crossed by the bridge, etc.).

.3 Vulnerability Assessment, in which the performance response of the infrastructure components are then assessed against the projected climate change events. It is in this step that prioritization is undertaken of the various distinct relationships between the infrastructure components, climate change events, operational and management policies and practices, so that only relationships/impacts ranked high are the ones meriting further analysis in Step 4, while relationships ranked low may be ignored.

Priority of Climate Effect (Tables 2-3 and 2-4)

The priority of Climate Effect P_C is an index of the level of risk due to extreme climate event and it determines whether the infrastructure component is vulnerable or not (PIEVC 2008).

$P_C = S_C * S_R$ (2-1)

where: S_C is probability Scale Factor for climate effect

S_R is probability Scale Factor for response effect

$P_C < 12$: component plus climatic effect eliminated from further evaluation (2-2)

$12 < P_C < 36$: potential vulnerability, further quantitative analysis required (2-3)

$P_C > 36$: vulnerability identified, recommendations required (2-4)

Table 2-3 Probability Scale Factor for Climate Effect (S_C) – (PIEVC 2008)

Scale	Probability
0	Negligible/Not Applicable
1	Improbable/Highly Unlikely
2	Remote
3	Occasional
4	Moderate/Possible
5	Often
6	Probable
7	Certain/Highly Probable

Table 2-4 Scale Factor for Response Effect (S_R) – (PIEVC 2008)

Scale	Severity of Consequences and Effects
0	Negligible or Not applicable
1	Very Low/Unlikely/Rare/Measurable change
2	Low/Seldom/Marginal/Change in serviceability
3	Occasional – Loss of some capacity
4	Moderate – Loss of some capacity
5	Likely regular/Loss of capacity and some function
6	Major/Likely/Critical/Loss of function
7	Extreme/Frequent/Continuous/Loss of asset

.4 Indicator Analysis, in which the capacity of the infrastructure components today are matched against today's loads – including climate change loads, and future, dwindling, capacity of the infrastructure components are matched against projected future climate change loads. Here, either a component has greater capacity than the demand imposed on it or it is facing a demand in excess of its capacity now or in the future. If the conclusions reached in this step are inconsistent with what logic would suggest, data and other statistical inputs need to be re-examined before going forward.

.5 Recommendations, in which the infrastructure is given a pass; or a need for intervention by way of rehabilitation/upgrading is the verdict; or management intervention by way of new policies for operating, managing, and maintaining the infrastructure would rectify present or future problems; or there is insufficiency in the quantity and/or quality of available data to reach a reliable conclusion.

The PIEVC protocol is for a one-time *impacts assessment*; it does not provide for the *continuous management* of infrastructure against the impacts of climate change. For example, measures against which a bridge has high resilience are neglected, making it impossible to rank that bridge against another bridge that is (very) vulnerable against the same measure. Further, the protocol does not have as its objective the development of a points-system for rating highway bridges or other types of public infrastructure against climate change impacts, nor does it have within its scope the incorporation of climate change impacts into a Bridge Management System. The protocol does not distinguish between the consequence of a climatic impact on a structure, on one hand, and a scaled cost to the road users, on the other hand. The protocol does not provide the equivalence of a *Bridge Inspection Form*, which a transportation agency could use for scheduled inspections of their bridges. The methods proposed in this thesis address all of the above.

2.5 Magnitude of Climate-Triggered Extreme Load that produces Bridge Collapse

2.5.1. Scour

FHWA (2011) identifies scour as an important climate-triggered loading and NCHRP Report 489 (TRB 2003) specifies provisions for the design of highway bridges against extreme event loads and extreme event load combinations. The report does not provide a procedure for the design or evaluation of reinforced concrete piers in bridges subjected to extreme loads or extreme load combinations distinct from the procedure for their design against non-extreme loads. But the report does note that concrete columns in bridge bents are subjected to lateral loads caused by extreme events in addition to vertical (gravity) dead and live loads. Further, the report (TRB 2003) asserts that the failure of a concrete pier under the action of extreme lateral loads will most probably be due to bending. Finally and most importantly, the report (TRB 2003) recommends a load combination involving dead load, live load, and scour depth as follows (TRB 2003):

$$\text{Load Combination} = 1.25DC + 1.75LL,\ 1.8SC \qquad (2\text{-}5)$$

Where:

DC is dead load, LL is live load, and SC is the nominal depth of scour in feet. It is important to note that Equation (2-5) is not easily useable for the scour rating of an existing bridge, because it would be too late to locate the foundation at the specified scour depth of 1.8*Scour-Depth. It is also important to note that Eqn. (2-5) is meant for the design of foundation and substructure elements at the ultimate limit state, with a further requirement that a factor of 1.8 be applied to the nominal pier scour depth that has been determined by geotechnical and structural analysis.

FHWA` (2012) cites scour as the most common cause of bridge failures. In 1987, 17 bridges in New York and New England were either damaged or destroyed by scour, just as a 1985 flood destroyed 73 bridges in Pennsylvania, Virginia, and West Virginia (FHWA 2012). Over 500 bridges sustained damages attributed to scour in a 1994 storm that swept through the State of Georgia. Thirty-one of those bridges sustained 5 to 7 metres of stream contraction scour in addition to local scour, and had to be replaced. Of an additional 150 bridges identified as scour-damaged, 73 had a recommendation for repair or replacement. The total loss in highway infrastructure associated with the 1994 flooding was estimated at $130 million (FHWA 2012). These and similar losses that preceded them, together with the sheer fact that over 500,000 highway bridges in the United States are water crossings, led to the recommendation by AASHTO that *pile length should be determined in all cases such that the design structural load is entirely supported below the calculated scour depth* (FHWA 2012). Finally, FHWA (2012) notes that the added cost of making a bridge less vulnerable to scour-triggered failure is small compared to the total cost of bridge failure, which can easily reach 2 to 10 times the cost of the bridge itself.

Khelifa et al. (2013) proposed a climate-based risk model that could be incorporated into asset management systems for the prioritization of maintenance, repair, and replacement schedules in the United States. The input, which included the *dollar value of human life* and *detour length*, were deployed in the Federal Highway Administration's *HYRISK* model for the risk-assessment of bridge collapse due to scour. The study depended on the 2009 National Bridge Inventory (NBI) database and the data are presented state-by-state as opposed to by individual infrastructure asset. Notwithstanding the foregoing, when applied to all bridges crossing water in the United States, the model predicts that economic losses due to climate change factors will increase by 15% over current losses and that the expected annual bridge failures will increase by at least 10% over current failures.

Noting that currently the majority of bridge failures in the United States are due to scour, Khelifa et al. (2013) report that what is often omitted in bridge risk assessment is the risk of bridge failure due to scour. Finally, noting that their study was primarily aimed at a state-by-state comparison of scour-vulnerability of bridges, the authors (Khelifa et al. 2013) caution that their method should not be used for projects prioritization within an inventory or jurisdiction.

To conclude this discussion of scour-vulnerability of highway bridges, it should be noted that coastal bridges present extra and special problems relative to river bridges and the approach to the vulnerability issues of coastal bridges in the presence of extreme events are discussed in FHWA (2008b).

2.5.2. Ice Accretion

The Canadian Highway Bridge Design Code S6-14 (Canadian Standards Association 2014) provides for a design load combination involving wind and ice accretion loads as follows.

$$\text{ULS Combination } 7 = \alpha_D{*}D + \alpha_E{*}E + \alpha_P{*}P + 0.75W + 1.3A \qquad (2\text{-}6)$$

Where:

D, E, and E are permanent loads; W is wind load; and A is ice accretion load

It should be noted that although Equation (2-6) is good for design or evaluation of a structural member, it can’t be used for determining the magnitude of ice accretion load that would produce failure of the member in the presence of live load. Therefore, it is necessary to devise a method for determining the said failure load.

AASHTO (2015), on the other hand, has no general design provisions for bridges under ice accretion loading because ice accretion is deemed a site-specific loading. However, the Code does allow that, in combination with ice accretion load, a reduced level of live load should be used due to the dictates of the driving conditions.

2.6 Summary

Based on the literature review presented above, the following observations are made.

1. <u>Multi-Criteria Ranking:</u> The consensus reported in literature is that it is desirable and would indeed be useful if a way could be found to consider all the identified criteria (bridge performance, utility, user cost, and extreme events) in the optimization of bridge projects’ selection in Bridge Management Systems. So far, the best solution available is to optimize based on performance first, and then *may be* on utility. There

is no evidence in literature of a previous attempt at developing a ranking method in which tradeoffs are rendered redundant and there is no prejudgment of the relative importance of one criterion with respect to another.

2. Vulnerability to Climate-Triggered Extreme Events: There is very little information available in literature on the ways to rate highway bridges against climate change impacts. But Engineers Canada (Canadian Council of Professional Engineers) in 2008 developed a protocol for a *one-time assessment* of the vulnerability of public engineering infrastructure against climate change impacts (PIEVC, 2008). The protocol provides for an assessment of highway bridges against climate change vulnerability, but it discounts bridges that are resilient, thus, making it impossible to compare the rating of all the bridges in the inventory. Further, contemplating only a one-time assessment, the protocol does not support a continuous management of the vulnerability or resilience of highway bridges in a bridge inventory. There is a need for formulating a method for the climate change vulnerability rating of highway bridges suitable for the continuous management of a highway bridge inventory within a Bridge Management System.

3. Vulnerability to Climate-Triggered Extreme Load: There are provisions in both the Canadian Highway Bridge Design Code and the AASHTO Bridge Design Specifications for designing against scour. The former code also has provisions for structural design accounting for ice accretion load. But there are no provisions in any of the two codes, or anywhere else, for determining the magnitude of scour or ice accretion loading that would cause failure of the bridge.

The proposed research attempts to advance the state-of-the art by addressing some of the research gaps identified above.

Chapter 3

Research Methodology and Data Collection

3.1. Introduction

As earlier indicated, the thesis comprises the following three major topics and each requires a different technique of investigation: (a) climate change resilience rating of highway bridges, (b) determination of the magnitude of climate-triggered extreme load that would produce the collapse of a highway bridge, and (c) multi-criteria ranking method for the selection of bridge projects in a Bridge Management System. In all three cases, the guiding principle adopted for the development of the methodologies is objectivity, which is achieved by eliminating pre-conceived hierarchies among competing bridge preservation strategies, project alternatives, criteria, or outcomes.

As an example, freeboard is important for all water crossings: the greater the clearance below the bridge, the less vulnerable the bridge to abutment washout and deck flooding. Therefore, a measure of the clearance below the bridges is an objective measure of their resilience to abutment washout and deck flooding. As another example, for multi-criteria ranking of bridge projects, all criteria are considered each important enough to dictate the implementation of a bridge project ahead of other bridge projects. In other words, all criteria are equally important and what separates the projects is how well they score on each of the criteria relative to one another. This means that Criterion “P” is neither superior nor inferior to Criterion “Q”.

The other cardinal attribute of the methods is generality and adaptability. For example, while the method for multi-criteria ranking is demonstrated for highway bridge infrastructure, it is generally applicable in many other fields. It follows that the methods will have the capacity to be extended to countless number of criteria, or adapted for highway bridges in other climates, or applied to other types of extreme loads.

With the above guiding principles and the following definitions, the methods developed for the study of the management of highway bridges against climate change impacts, and for combining climate change criteria with the traditional bridge management criteria, are presented below.

3.2. Definitions

The following definitions are relied upon for the development of the research methodology for this thesis.

Infrastructure resilience *is the ability to reduce the magnitude and/or duration of disruptive events. The effectiveness of a resilient infrastructure or enterprise depends upon its ability to anticipate, absorb, adapt to, and/or rapidly recover from a potentially disruptive event* (National Infrastructure Advisory Council 2009).

Vulnerability *is the intrinsic property of a system resulting in susceptibility to a risk source that can lead to an event with a consequence* (ISO 2009). In other words, vulnerability is a condition of the system and a measure of the system's susceptibility to threat scenarios (Ezell 2005).

Risk is *the potential for an unwanted outcome resulting from an event, which is determined by the product of: (a) the likelihood of the impact, and (b) the consequence of the impact* (Federal Highway Administration 2011a).

Optimization is *a state of the system at which the best possible compromise between opposing tendencies is attained* (The Concise Oxford Dictionary 1990). A second definition is that *optimization is the maximization of benefits under constraints* (Von Neumann and Morgenstern 1964).

General Purpose of Engineering: *the aim of any purposeful activity is optimization of the outcome; in particular, the purpose of engineering design is to maximize the utility to be derived from the system produced* (Newmark and Rosenblueth 1971).

Bridge Performance (or, bridge condition index BCI) *is defined as the primary objective measure for highway bridge rating and includes the structural and operational safety and functionality of the bridge* (Department of Highways & Public Works of Yukon 2010).

Utility (or, agency benefits) *is defined as cost savings per unit cost of a highway bridge project accruing from an early implementation of a project compared to postponing the project to the end of the planning horizon when further deterioration would attract a larger scope and a larger cost* (Department of Highways & Public Works of Yukon 2010).

3.3. Data Collection

The data used for demonstrating the new methods proposed in this thesis came from the following sources.

a. Yukon Bridge and Culvert Condition Report 2010 (Yukon Highways and Public Works 2010).
b. Records of As-Built Drawings for fourteen Yukon highway bridges (Yukon Highways and Public Works 2010).
c. Site visits to numerous Yukon highway bridges, including the fourteen bridges studied for this thesis.
d. Photographs of the fourteen highway bridges, taken during site visits.
e. Surveys of highway bridge engineers, who were asked to use their knowledge and expertise to rank bridge intervention criteria. Respondents comprised a mix of Chief Bridge Engineers in the Provinces and Territories of Canada and Technical Committee members of the Canadian Highway Bridge Design Code.

3.4. Climate Change Resilience/Vulnerability Rating of Highway Bridges

3.4.1 General

Among other objectives, this thesis sets out to answer the question of how the science of climate change could be reduced to practical engineering measurements or measures that a bridge engineer could deploy towards the management of a bridge inventory against climate-triggered extreme events. The above objective quickly led to the question of what measurements the engineer should make on site during a scheduled annual or biannual inspection. For example, what measurement would determine the susceptibility of the bridge to flooding? Should the measure be the size of the bridge opening or should it be the vertical clearance below the bridge relative to the 100-year flood water elevation?

As noted in Chapter 2, the three components of quantitative risk assessment are hazard analysis, vulnerability analysis, and consequences analysis (Zhu and Frangopol 2013). This approach is applied in this thesis to the development of the methodology for the resilience/vulnerability rating of highway bridges to climate-triggered extreme events.

Hazard Analysis

Hazard analysis involves identification of the candidate extreme events that could occur at a bridge site in the climatic region where the bridges are located. For the Canadian Arctic, such events would include flooding induced by melting ice, the melting of permafrost underneath bridge foundations, ice accretion on bridge superstructure, pier and abutment scour associated with channel flooding, etc. Some of these extreme events could be detrimental to the resilience of more than one component of the bridge structure.

Vulnerability Analysis

Vulnerability analysis identifies the components of the bridge that are susceptible to one or more climate-triggered extreme events, states the nature of the impact of the extreme event on the bridge component, and indicates the mechanism of the vulnerability. For this study, vulnerability of the various components of the bridges is identified by determining *Resilience*

Indicators (RI). These indicators will be as many or as few as may be dictated by information generated at the hazard analysis stage.

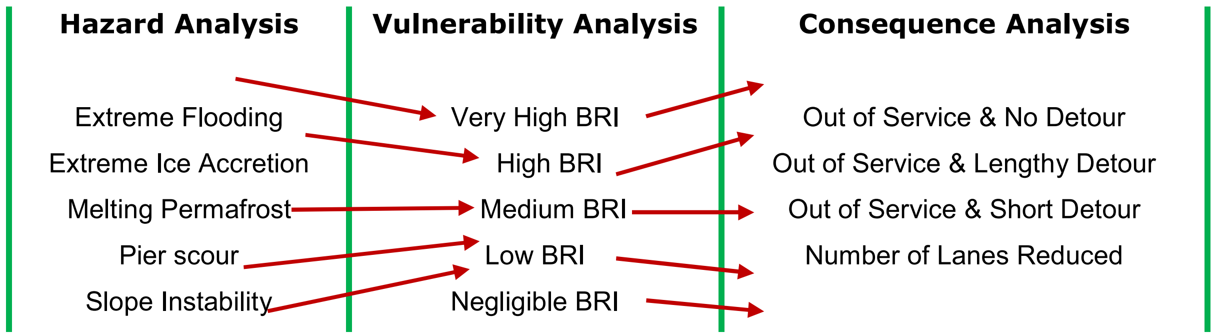


Fig. 3-1 Risk Assessment Model for Highway Bridges subjected to Extreme Climate Event

The other half of vulnerability analysis involves the identification of capacity measures, which indicate how well a bridge is equipped to withstand the projected climatic effects. The capacity measures could be as many or as few as may be dictated by the selected bridge resilience indicators. Finally, the association of Resilience Indicators and Capacity Measures (Table 3-1) is required in order to proceed with the calculation of the BRI.

Consequence Analysis

Risk has two components, the *severity or likelihood* of the event, on the one hand, and the *consequence* of that event occurring, on the other hand. If the vulnerability (severity of the event) is high and the consequence is dire, the result is very high risk. Conversely, low vulnerability combined with negligible consequence yield very low risk. The definition adopted in this study is that risk (R) is a product function of severity (vulnerability V) of an event and the consequence (C) of the event as depicted in Eqn. (3-1).

$$R = V * C \tag{3-1}$$

3.4.2 Model for Evaluation of Resilience Indicators

Conceptually, each resilience indicator is a product of the resilience indicator *weight* and the capacity measure *rating* as shown in Equation (3-2). But how would the weights be determined? The Ontario and Quebec Bridge Management Systems (Thompson et al. 2003, Ellis et al. 2008), both determine weights assigned to bridge components based only on the initial cost of the components. Here, it is proposed to determine the weights assigned to the various resilience indicators on the basis of not only the initial cost of the components affected by the indicator, but also the consequence for the serviceability/availability of a bridge when impacted by the climate-triggered event, as well as the attendant cost/inconvenience to the road users (Equation 3-3). The underlying concept is that expensive components should be assigned higher weights because it would cost more to replace or rehabilitate them. Since the weight of the resilience indicators identified for a specified bridge must sum up to 100%, a higher-weighted bridge component that rates low on the associated capacity measure results in a decrease of the *bridge resilience* (*Resilience* percent), signaling the need for urgent action. An example of a higher-weighted bridge component is the Abutment (on which the abutment washout resilience indicator is based). The associated capacity measure would be the bridge's hydraulic capacity.

To recap, the model will comprise resilience indicator *weights* and capacity measure *rating*. A general example each of RI *Weight Parameters* and capacity measures *Rating Guide* is shown in Tables 3-2 and Table 3-3, respectively. The remaining task, then, is to apply the method to the climate change resilience rating of highway bridges in the Canadian Arctic. This is done in Chapter 4.

$$W(x) = (\alpha\beta\Phi)_i / \sum_{i=1}^{i=n} \alpha_i \beta_i \Phi_i \, (x) \tag{3-2}$$

$$BR(W, R) = \sum_{i=1}^{i=n} W(x_i) * R(x_i) \tag{3-3}$$

where

W is the weight calculated for each resilience indicator (RI)

R is the rating of the bridge on the capacity measure associated with RI

BR is the *Bridge Resilience* calculated as summation over all RI's of the product of W and R

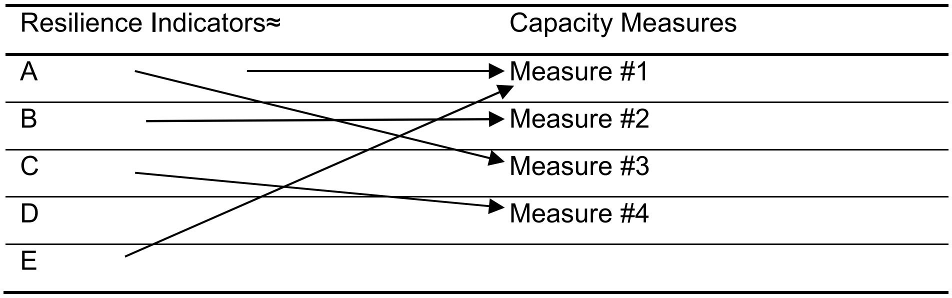
x_1 to x_n are the resilience indicators identified for each bridge

α denotes the cost of the bridge component affected by the climate-triggered extreme event

β denotes the consequence of the climate-triggered extreme event on the serviceability/availability of the bridge

Φ denotes the cost or inconvenience to the road user if the bridge performance or availability is compromised when the bridge experiences the extreme event

Table 3-1 Association of Resilience Indicators with Capacity Measures (*General*)



Resilience Indicators≈	Capacity Measures
A	Measure #1
B	Measure #2
C	Measure #3
D	Measure #4
E	

≈ A, B, C, D, and E are the Resilience Indicators identified for the specified bridge

Table 3-2 Weight Parameters' Guide (*General*)

Weight Parameter 1 ($\boldsymbol{\alpha}$)	Weight Parameter 2 ($\boldsymbol{\beta}$)	Weight Parameter 3 ($\boldsymbol{\Phi}$)
Scaled Score 1 (Max)	Scaled Score 1 (Max)	Scaled Score 1 (Max)
Scaled Score 2	Scaled Score 2	Scaled Score 2
Scaled Score 3	Scaled Score 3	Scaled Score 3
Scaled Score 4	Scaled Score 4 (Min)	Scaled Score 4
Scaled Score 5 (Min)	0 (Zero): N/A¥¥	Scaled Score 5 (Min)
0 (Zero): N/A¥¥		0 (Zero): N/A¥¥

¥¥ Not Applicable

Table 3-3 Rating Guide for *Capacity Measures* – 2070's Demand – (*General*)

Capacity Measure **X**	Capacity Measure **Y**	Capacity Measure **Z**
Scaled Rating 1 (Max)	Scaled Rating 1 (Max)	Scaled Score 1 (Max)
Scaled Rating 2	Scaled Rating 2	Scaled Score 2
Scaled Rating 3	Scaled Rating 3	Scaled Score 3
Scaled Rating 4 (Min)	Scaled Rating 4 (Min)	Scaled Score 4 (Min)
–: Not Applicable	–: Not Applicable	–: Not Applicable

For the present study, the *resilience indicators* proposed as representative of all the climate-triggered, non-bridge-condition indicators are:

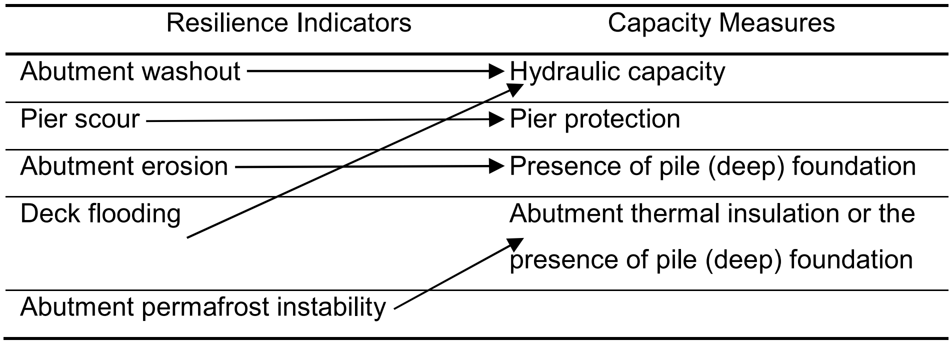
a. abutment washout
b. pier scour
c. abutment erosion
d. deck flooding
e. abutment permafrost stability

The corresponding *capacity measures* against which the bridge is to be rated in determining the resilience indicators are:

i. hydraulic capacity
ii. pier scour protection
iii. abutment thermal insulation or the presence of pile (deep) foundation
iv. slope/foundation stability

The association of resilience indicators and capacity measures are as shown in Table 3-4. <u>It should be noted that</u> the capacity measure of *slope/foundation stability* has no resilience indicator association in this study.

Table 3-4 Association of Resilience Indicators with Capacity Measures



Resilience Indicators	Capacity Measures
Abutment washout	Hydraulic capacity
Pier scour	Pier protection
Abutment erosion	Presence of pile (deep) foundation
Deck flooding	Abutment thermal insulation or the presence of pile (deep) foundation
Abutment permafrost instability	

The Flowchart of Fig. 3-2 illustrates the procedure for calculating climate-related bridge resilience indicators for any bridge in an agency's inventory. The first step in calculating bridge resilience indicators is determining the relative importance (i.e. the *weight* percentage) of each indicator. Climate impacts on the more expensive/important components of the bridge, impacts that have the more dire consequences for the serviceability/availability of the bridge, and impacts that manifest the most inconvenience for the traveling public and the connected communities, are assigned the higher weights. For each bridge, the total Weight % for all the indicators combined must come to 100%.

A suggested scoring of the three weight parameters α, β, and Φ is shown in Table 3-5, while examples of the calculation of weights for two of the 14 bridges used in illustrating the proposed method are presented in Tables 3-6 and 3-7. Using the values of α, β, and Φ, the Weight % is calculated for each of 5 indicators as shown in the Flowchart.

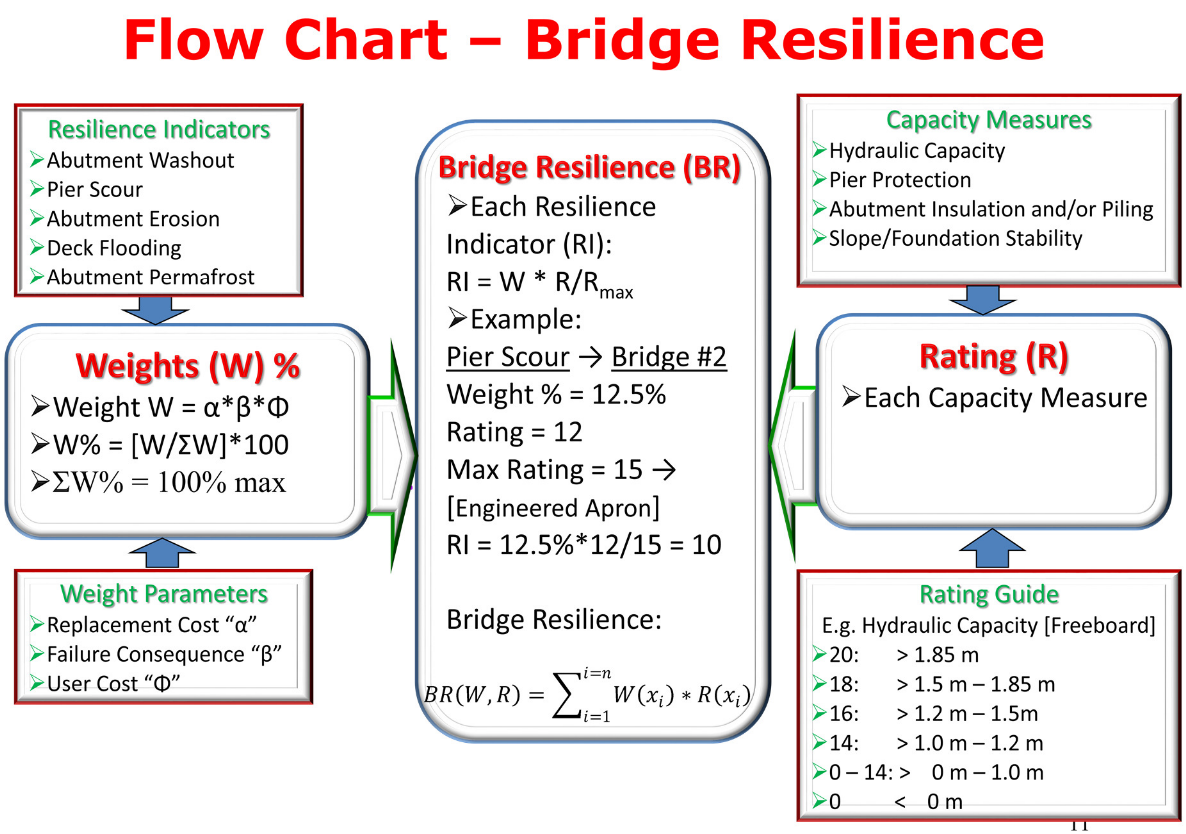
As shown in Table 3-6, the scoring of the weight parameters is on a scale of 5 to 0, with 5 denoting the greatest importance, the most dire consequence, or the most inconvenience to the public; while 0 denotes the least importance in terms of Agency cost, the least severe consequence, or the least inconvenience to the public.

The Weight Factor for each resilience indicator is calculated as the product of the 3 weight parameters for that indicator, while the Weight percentage (%) for each indicator is calculated as the ratio of the Weight Factor for that indicator to the sum of the Weight Factors for all 5 indicators.

The weight parameter of *User Cost* merits a brief discussion. The philosophy behind the scoring shown in Table 3-5 is the following. An abutment washout is an extreme event, which renders a bridge unavailable to the public since the event likely causes collapse of the bridge. Where that happens and there is no detour route available at all, the maximum score of 5 is assigned as the weight parameter score for abutment washout. But one may ask why not also assign the score of 5 to Pier Scour, or couldn't pier scour also result in the collapse of a Bridge? The answer to that question is that pier scour happens all the time on a bridge if pier protection is absent, but it is less likely to be an extreme event (as an abutment washout is). It is, rather, a gradual event, more likely to be captured by bridge inspections. Further, the *Weights* are but one of 2 components of the calculated bridge resilience indicator; the other half is the *Rating*.

It follows that if pier scour is observed by inspections to have continued to worsen over the years, the bridge would have a low pier scour rating and that would result in a low bridge resilience indicator for that bridge based on the pier scour component of the calculated bridge resilience indicator. Therefore, because we can't say that a bridge collapses each time pier scour happens, it is *Rating* that is used for determining whether the bridge is adequately protected against pier scour or not. If the bridge has excellent pier scour protection, then the method is designed to keep the Weight down and keep the Rating high, both of which are in accord with the stated philosophy of the method, namely, to assign higher weights to climate events that cause the most dire consequence or the most inconvenience to the public while assigning higher ratings to bridges that are resilient against climate-triggered extreme events.

The other half of the procedure for obtaining the bridge resilience indicators consists of the calculation of the capacity rating of the bridge on each capacity measure that corresponds to each of the 5 resilience indicators. For each capacity measure, a proposed *Rating Guide* is provided (Table 3-8). Using as-built drawings, a bridge inspector can rate the bridge during an inspection visit to the bridge site. The capacity measures rating, together with resilience indicator weights, can then be used to determine the bridge resilience against the various climate-triggered extreme events.



Flow Chart – Bridge Resilience

Resilience Indicators

- Abutment Washout
- Pier Scour
- Abutment Erosion
- Deck Flooding
- Abutment Permafrost

Weights (W) %

- Weight W = α*β*Φ
- W% = [W/ΣW]*100
- ΣW% = 100% max

Weight Parameters

- Replacement Cost “α”
- Failure Consequence “β”
- User Cost “Φ”

Bridge Resilience (BR)

- Each Resilience Indicator (RI):

$RI = W * R/R_{max}$

- Example:

Pier Scour → Bridge #2

Weight % = 12.5%

Rating = 12

Max Rating = 15 → [Engineered Apron]

RI = 12.5%*12/15 = 10

Bridge Resilience:

$$BR(W,R) = \sum_{i=1}^{i=n} W(x_i) * R(x_i)$$

Capacity Measures

- Hydraulic Capacity
- Pier Protection
- Abutment Insulation and/or Piling
- Slope/Foundation Stability

Rating (R)

- Each Capacity Measure

Rating Guide

E.g. Hydraulic Capacity [Freeboard]

- 20: > 1.85 m
- 18: > 1.5 m – 1.85 m
- 16: > 1.2 m – 1.5m
- 14: > 1.0 m – 1.2 m
- 0 – 14: > 0 m – 1.0 m
- 0 < 0 m

Fig. 3-2 Flow Chart – Calculation of Bridge Resilience

In the case of the *Hydraulic Capacity* measure (Column 1 of Table 3-8), the standard adopted for this study is the 1.5 meters freeboard required by the Canada *Navigable Waters Protection Act* (Government of Canada 1985) for a 100-year flood. However, all 4 capacity measures are assessed against the demands of the extrapolated climate conditions of the last quarter of this century (2070's), which are higher than today's demands (ACIA 2004). That means that for hydraulic capacity, the 14 bridges reported in this paper are assessed against 1.85 meters for the 2070's, being the sum of 1.5 meters and the projected sea level rise in the Canadian Arctic of 350 mm over the first 7 decades of this century.

3.4.3 Procedure for determining Bridge Resilience (BR)

The following are the steps for deriving the bridge resilience indicators.

1 Identify climate-triggered extreme events that could occur at a highway bridge site.

2 Identify what components of the bridge would be affected.

3 Establish associations between each extreme event-type and the affected bridge component.

4 Name the indicators (bridge resilience indicators) of the bridge's resilience or vulnerability with respect to each event-type.

5 Propose a *Scoring Guide* (a schedule of numerical scores) for the three weight parameters of *initial cost* of the bridge component impacted, the *consequence* for the serviceability/availability of the bridge if the climate-triggered extreme event occurs, and the *cost* to the road users expressed as the degree of inconvenience for the traveling public and the connected communities when the bridge is impacted by an extreme climate event associated with the resilience indicator under consideration. Such a schedule of weight parameters is proposed and presented in Table 3-5.

6 Propose a mathematical formula for calculating the weight to be assigned to each resilience indicator to capture the relative importance of the bridge component that would be affected by the resilience indicator under consideration, the failure/serviceability consequence, and the user cost/inconvenience. The formula proposed is the following product function.

$$W(x) = (\alpha\beta\Phi)_i / \sum_{i=1}^{i=n} \alpha_i \beta_i \Phi_i \, (x) \tag{3-4}$$

Where: W is the weight calculated for each resilience indicator

x_1 to x_n are the resilience indicators identified for each bridge

α = Cost of the bridge component directly affected by the resilience indicator

β = Consequence for the bridge when a component is impacted by a climatic event

Φ = Cost to the users – the traveling public – if the bridge health, performance, or availability is compromised when the component is impacted by a climatic event

The above formulation was selected because it simply and accurately discriminates between the various intensities of impacts on *agency cost*, *serviceability consequence*, and *user cost*. For example, if there were 2 scenarios, each with a 5 out of 5 score on *Cost*, but 2 out of 5 score on *Consequence* for Scenario #1 and 1 out of 5 score on *Consequence* for Scenario #2, then the product function has a value of 10 (i.e. 5 * 2) for Scenario #1 and 5 (i.e. 5 * 1) for Scenario #2.

It can be seen that the product function accurately captures the fact that the first scenario is 100% *more consequential* than the second, while also capturing the fact that the scores are equal (5 and 5) for both scenarios on the *Cost* factor. Further, Scenario #1 is 100% (2:1) *more consequential* and also 100% (10:5) *more cost-consequential*, while coming in (5:5) *evenly costly* with Scenario #2.

7 Identify the relevant capacity measures.

Table 3-5 Weight Parameters' Guide

¥ Replacement Cost α	Consequence of Event β	User Cost Φ
5: 20% – 25%	5: Out of service	5: Out of Service & no detour
4: 15% – 20%	2.5: Needs immediate fix/replacement	3: Detour 300 to 500 km
3: 10% – 15%	2: Triggers deterioration	2.5: 150 to 300 km
2: 5% – 10%	1.5: Warrants testing or investigation	2: 0 to 150 km
1.5: 0% – 5%	0: N/A¥¥	1.5: Delays, number of lanes reduced
0: N/A¥¥		0: N/A¥¥

¥ Expressed as a percentage of the total initial construction cost of the bridge

¥¥ Not Applicable

Table 3-6 Weights for Resilience Indicators (RI) – Bridge #2

Resilience Indicator	¥ Replacement Cost α	Consequence of Event β	User Cost Φ	Weight Factor **WF = α*β*Φ**	Weight = $WF_i/\Sigma WF$
Abut Washout	4	5	2	40	44.3%
Pier Scour	5	1.5	1.5	11.25	12.5%
Abut Erosion	4	2	1.5	12	13.3%
Deck Flooding	5	2	1.5	15	16.6%
Abut Permafrost	4	2	1.5	12	13.3%
Total Weight					100.0%

¥ Expressed as a percentage of the total initial construction cost of the bridge
¥¥ Not Applicable

Table 3-7 Weights for Resilience Indicators (RI) – Bridge #4

Resilience Indicator	¥ Replacement Cost α	Consequence of Event β	User Cost Φ	Weight Factor **WF = α*β*Φ**	Weight = $WF_i/\Sigma WF$
Abut Washout	4	5	5	100	71.94%
Pier Scour	0	0	0	0	0%
Abut Erosion	4	2	1.5	12	8.63%
Deck Flooding	5	2	1.5	15	10.79%
Abut Permafrost	4	2	1.5	12	8.63%
Total Weight					100%

¥ Expressed as a percentage of the total initial construction cost of the bridge
¥¥ Not Applicable

8 Propose a scoring guideline for rating the bridges against each capacity measure. Such a *Rating Guide* is proposed and presented in Table 3-8. Table 3-8 can indeed be incorporated as a new section in a *Bridge Inspection Form*, to be used in rating highway bridges against climate change impacts.

9 Rate each bridge in the inventory against each capacity measure based on the *Rating Guide*.

10 Determine each bridge resilience indicator as the product of the *Weight* of that resilience indicator and the *Rating* of the bridge on the relevant *Capacity Measure*. Then sum up all the resilience indicator products to obtain the total bridge resilience score for the bridge as depicted in Equation (3-5).

$$BR(W,R) = \sum_{i=1}^{i=n} W(x_i)R(x_i) \tag{3-5}$$

<u>where</u>:

BR is the bridge resilience calculated for each bridge based on the specified resilience indicators for that bridge

W is the weight calculated for each resilience indicator

R is the rating of the bridge on the capacity measure associated with the resilience indicator under consideration

x_1 to x_n are the resilience indicators identified for each bridge

Table 3-8 Rating Guide for *Capacity Measures* (2070's Demand)

Hydraulic Capacity (Freeboard)	Pier Scour Resilience	Abutment Insulation
20: > 1.85 m	15: Engineered Apron	15: Piling + Blanket
18: > 1.5m – 1.85m	12: Adequate Riprap	13: Piling Only – New
16: > 1.2 m – 1.5 m	9: Some Riprap	11: Pad Fdn + Blanket
14: > 1.0 m – 1.2 m	6: No riprap; slow flow	8: Pad Fdn Only
0–14: >0 m – 1.0 m	3: No riprap; fast flow	6: Wood+Small Creek
0: < 0 m	0: No riprap; threatened	4: Wood+Fast Creek
	–: Not Applicable	2: Crumbling Wood

Table 3-9 shows the weight parameters for all the 14 bridges in the study while Table 3-10 shows inventory data for all 14 bridges.

Table 3-9 Weight Parameters for **All** 14 Bridges

Legend

α	Replacement cost of a bridge component affected by a climate-triggered extreme event
β	Consequence for a bridge of a climate-triggered extreme event at the bridge
Φ	Cost or inconvenience for the public caused by a climate-triggered extreme event at the bridge

	α	**β**	**Φ**	**α**	**β**	**Φ**	**α**	**β**	**Φ**	**α**	**β**	**Φ**
	Bridge #1			**Bridge #4**			**Bridge #7**			**Bridge #10**		
Abut Washout	3.5	5	5	4	5	5	4	5	4	5	5	4
Pier Scour	0	0	0	0	0	0	0	0	0	0	0	0
Abut Erosion	3.5	2	1.5	4	2	1.5	4	2	1.5	5	2	1.5
Deck Flooding	5	2	1.5	5	2	1.5	5	2	1.5	10	2	1.5
Abut Permafrost	3.5	2	1.5	4	2	1.5	4	2	1.5	5	2	1.5
	Bridge #2			**Bridge #5**			**Bridge #8**			**Bridge #11**		
Abut Washout	4	5	2	1.5	5	5	4	5	4	2	5	4
Pier Scour	5	1.5	1.5	5	1.5	1.5	0	0	0	5	1.5	1.5
Abut Erosion	4	2	1.5	1.5	2	1.5	4	2	1.5	2	2	1.5
Deck Flooding	5	2	1.5	5	2	1.5	5	2	1.5	8	2	1.5
Abut Permafrost	4	2	1.5	1.5	2	1.5	4	2	1.5	2	2	1.5
	Bridge #3			**Bridge #6**			**Bridge #9**			**Bridge #12**		
Abut Washout	3.5	5	5	4	5	5	2	5	5	4	5	2
Pier Scour	5	1.5	1.5	0	0	0	5	1.5	1.5	5	1.5	1.5
Abut Erosion	3.5	2	1.5	4	2	1.5	2	2	1.5	4	2	1.5
Deck Flooding	5	2	1.5	5	2	1.5	5	2	1.5	7	2	1.5
Abut Permafrost	3.5	2	1.5	4	2	1.5	2	2	1.5	4	2	1.5

	α	β	Φ	α	β	Φ
	Bridge #13			Bridge #14		
Abut Washout	5	5	4	5	5	4
Pier Scour	0	0	0	0	0	0
Abut Erosion	5	2	1.5	5	2	1.5
Deck Flooding	10	2	1.5	10	2	1.5
Abut Permafrost	5	2	1.5	5	2	1.5

Table 3-10 Inventory Data for the 14 Bridges

Bridge #	Year Built	Year Upgraded	# of Spans	Bridge Length (m)	100-Year Flood Freeboard (m)	Superstructure/ Substructure Type
1	2010	-	1	36.6	-0.10	Acrow Steel Bailey Steel H-Pile Foundation
2	1963	2009	4	74.0	0.71	Steel girders Steel H-Pile Foundation
3	2008	-	2	100.0	1.7	Welded steel girders Steel pipe pile foundation
4	2009	-	1	80.0	1.8	Welded steel girders Concrete-filled steel pipe pile foundation
5	2007	-	8	270.0	2.18	Prestressed concrete I-Girders, circular concrete pier stems, steel pipe piles
6	2006	-	1	68.0	1.50	Welded steel girders Steel H-Pile Foundation
7	1947	2005	1	61.2	3.585	Steel through-truss Steel pile foundation
8	1947	2005	1	48.8	1.50	Steel through-truss Steel pile foundation
9	1946	2006	3	89.4	2.30	2 Steel pony truss spans 1 steel girder approach span, 2 rectangular concrete piers Steel pile foundation
10	1963	2006	1	21.3	1.07	Welded steel girders Steel H-Pile Foundation
11	1944	2006	10	445.9	7.40	Deck truss Rectangular, tapered, concrete piers Steel pile foundation
12	1955	2007	2	152.4	2.50	Steel through-truss Rectangular concrete pier Steel pile foundation
13	1943	2010	1	18.8	1.345	Rolled steel girders Steel H-Pile Foundation
14	1944	2010	1	18.6	0.638	Rolled steel girders Steel H-Pile Foundation

3.5. Magnitude of Climate-Triggered Extreme Load that Produces Bridge Failure

One approach to accounting for climate-triggered extreme loading in highway bridge design or load evaluation would be to estimate or forecast the magnitude of *Ice Accretion* or *Pier Scour* loading, say, for a bridge site, then check if the bridge has adequate strength to withstand the estimated load. But that would not provide the answer to the question of what magnitude of climate-triggered extreme loading (e.g. ice accretion) would exhaust the strength reserve of the bridge. Therefore, for this research, the approach that would be pursued is to define/determine the reserve strength available to sustain extreme climate-triggered loading at a bridge site in the presence of un-factored live load and factored dead load.

Using this approach, the magnitude of climate-triggered extreme loading that would produce bridge collapse would is determined as the total factored live plus factored dead loads capacity of the bridge less the portion of that load capacity that resists the combined factored dead plus un-factored live loads. Finally, the strength difference is converted to a load intensity (thickness of ice in metres, depth of flood water versus height of exposed pier stem in metres, etc.) that would produce collapse of the bridge.

The flowchart of Figure 3-3 depicts more fully the methodology described above for the case of extreme pier scour load. The flowchart shows that various elevations will be required for evaluating the lever arm for the bending moment M_B produced by the Braking Force F_B. Those elevations are also used for determining the hydrostatic force and the resulting bending moments M_q in the pier. The flowchart also shows that the *pier scour vulnerability index* is the flood water depth h at pier bending failure, where h is determined by equating the braking force bending moment M_B to the hydrostatic bending moment M_q.

Similarly, Figure 3-4 depicts the methodology for extreme ice accretion load. Fig. 3-4 shows that an assumption of a uniform thickness of ice on all exposed steel truss members is captured with a uniform distributed load of 1 kN/m. The *most stressed member* (designated M_{ms}) is taken as the member with the largest axial force (designated F_1) under the above-specified loading. Next, the un-factored truck live load axial force (designated F_{ms}) in Member M_{ms} is calculated.

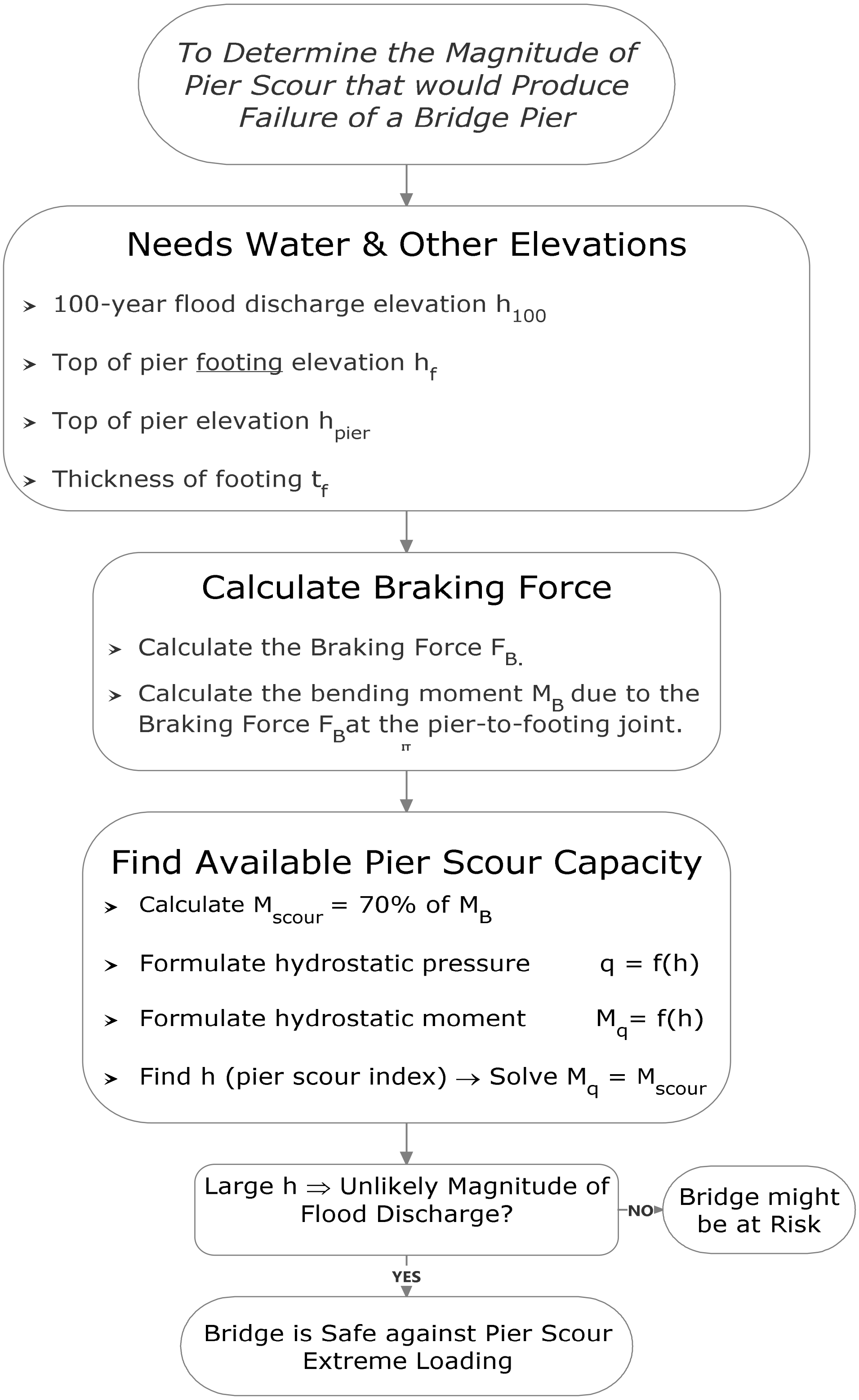


Fig. 3-3 Flow Chart for Analysis of Pier Scour Extreme Loading

The available extreme ice accretion axial force capacity (F_{ice}) is then calculated as 70% of F_{ms}. Next, by proportionality, the distributed ice accretion load (1 kN/m) and the corresponding axial force (F_1), on the one hand, are related to the limiting ice accretion axial force (F_{ice}) and the corresponding ice accretion intensity q_{ice}, on the other hand. Finally, by using the unit weight of ice (γ_{ice}), convert q_{ice} (kN/m) to the limiting thickness of ice (t_{ice}) in metres. To finish, the decision criterion is invoked to determine if the bridge is safe or unsafe against extreme ice accretion.

As an example, the data required for determining the magnitude of extreme pier scour loading that would collapse a bridge include: elevation of pier top, elevation of pier bottom, diameter of pier shaft, top of pier footing elevation, thickness of pier footing, river bed elevation, depth from riverbed elevation to top of footing, and the design flood discharge (usually 100-year flood discharge). Most of the above-cited information would normally be available on “As-Built” drawings and/or Bridge Inspection records maintained by the transportation agency.

All structural analysis for ice accretion and pier scour referenced here and in Chapter 5 was undertaken using the commercially available structural analysis software *CSiBridge* (Computers & Structures Inc. 2014). The software is a finite element based structural analysis program with linear and non-linear analysis capabilities. It has built-in boundary conditions (restraints, constraints, and connection types as well as standard and custom-specified steel and concrete structural sections and shapes. Concrete deck is modelled as a shell element and the user simply has to specify the thickness of the deck as well as reinforcing and prestressing steel details. The steel truss members were modelled as steel frame elements whereas concrete piers and abutments were modelled as concrete frame elements. All analysis were linear-elastic.

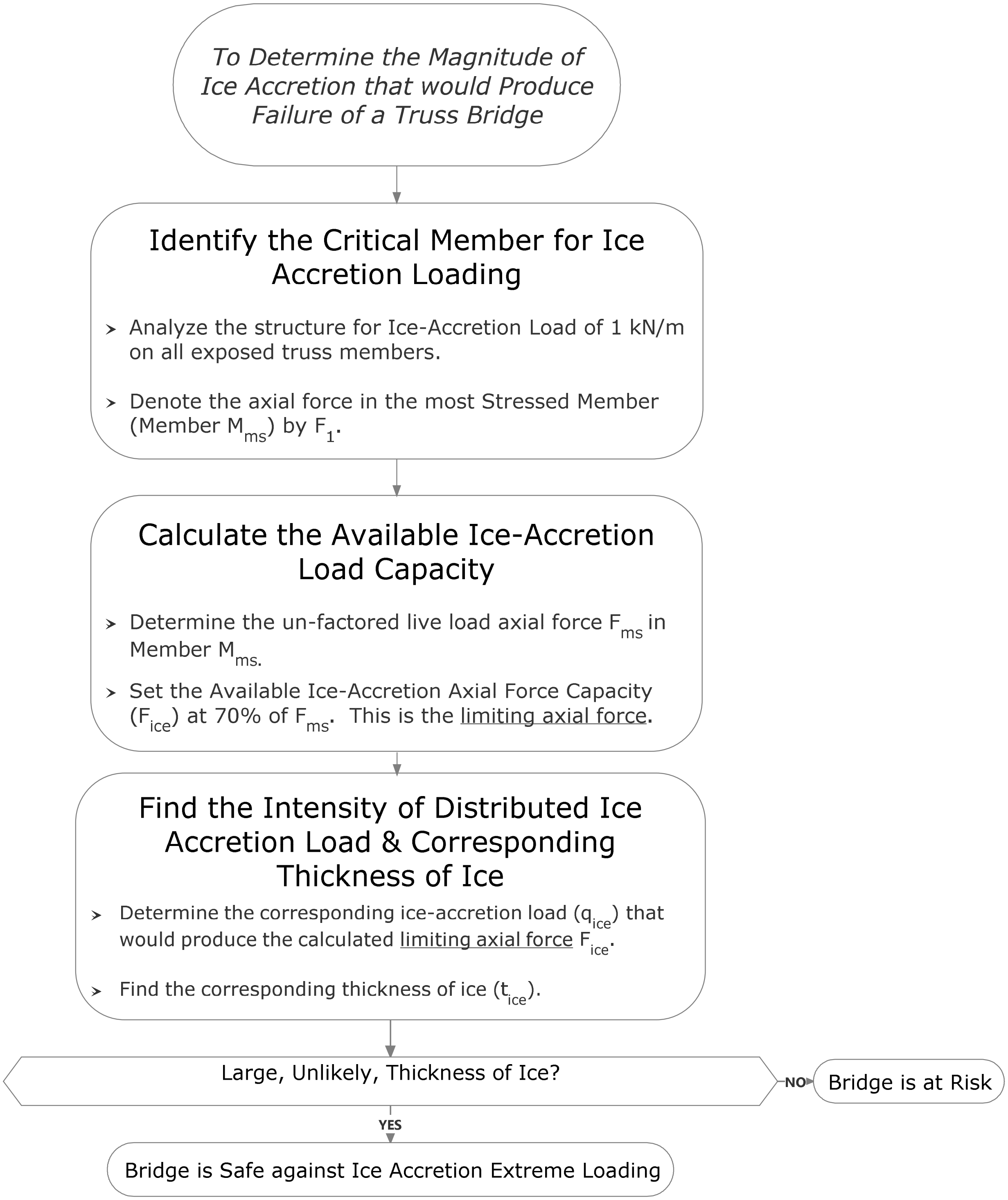
The *CSiBridge* software is used by bridge structural engineering offices all over Canada and the United States, which means that it comes ready to use, so that the user does not have to define the type of finite elements to use for the various types of frame/shell members comprising the bridge structure for example.

3.5.1 Pier Scour Extreme Load

The major parameters involved in the calculation of the scour load capacity for a bridge pier are illustrated in Fig. 3-5. These parameters are the top of pier elevation (h_{pier}), the 100-year flood elevation (h_{100}), river bed elevation (h_g), and the top of footing elevation (h_f). These elevations are annotated in Fig. 3-5.

a. Assumptions

1. Since pier scour causes increased exposure of the pier stem to hydrostatic-pressure and the resulting bending moments, the bending capacity of the pier is selected as the criterion for evaluating the magnitude of pier scour that would produce failure of the pier.
2. The braking force load case is assumed to be the sole basis for the concrete pier's bending strength design.
3. For simplicity, the effect of hydrostatic forces on the downstream face of the pier is neglected in the analysis.



To Determine the Magnitude of Ice Accretion that would Produce Failure of a Truss Bridge

Identify the Critical Member for Ice Accretion Loading

- Analyze the structure for Ice-Accretion Load of 1 kN/m on all exposed truss members.
- Denote the axial force in the most Stressed Member (Member M_{ms}) by F_1.

Calculate the Available Ice-Accretion Load Capacity

- Determine the un-factored live load axial force F_{ms} in Member $M_{ms.}$
- Set the Available Ice-Accretion Axial Force Capacity (F_{ice}) at 70% of F_{ms}. This is the limiting axial force.

Find the Intensity of Distributed Ice Accretion Load & Corresponding Thickness of Ice

- Determine the corresponding ice-accretion load (q_{ice}) that would produce the calculated limiting axial force F_{ice}.
- Find the corresponding thickness of ice (t_{ice}).

Large, Unlikely, Thickness of Ice?

Bridge is at Risk

Bridge is Safe against Ice Accretion Extreme Loading

Fig. 3-4 Flow Chart for Analysis of Ice Accretion Extreme Loading

b. Magnitude of Pier Scour producing Failure of a Concrete Pier

The following steps are required for determining the magnitude of pier scour that would produce the failure of a bridge pier (Figures 3-3 and 3-5).

1. From As-Built drawings, extract the 100-year flood water elevation (h_{100}) and the elevation of top of pier footing (h_f). Elevation (h_{100}) will be assumed to be the highest elevation that the water will reach under the design flood discharge for the bridge.
2. Determine the braking force F_B applied on the pier based on the length of the span supporting the truck and in accordance with the provisions of the Canadian Highway Bridge Design Code (Canadian Standards Association 2014). The Code formula for calculating the braking force in a span is 180 kN + 10% of (9 kN/m)*Span Length, which shows that the braking force is a function of the span length only. This braking force is to be divided between the two supports of the said span.
3. Calculate the un-factored (nominal) bending moment M_B at the pier-to-footing joint when the braking force F_B is applied at the top of the pier.
4. Assume the available pier scour load capacity for the pier to be 70% of the un-factored braking force bending moment M_B, and denote this moment capacity by M_{SCOUR}.

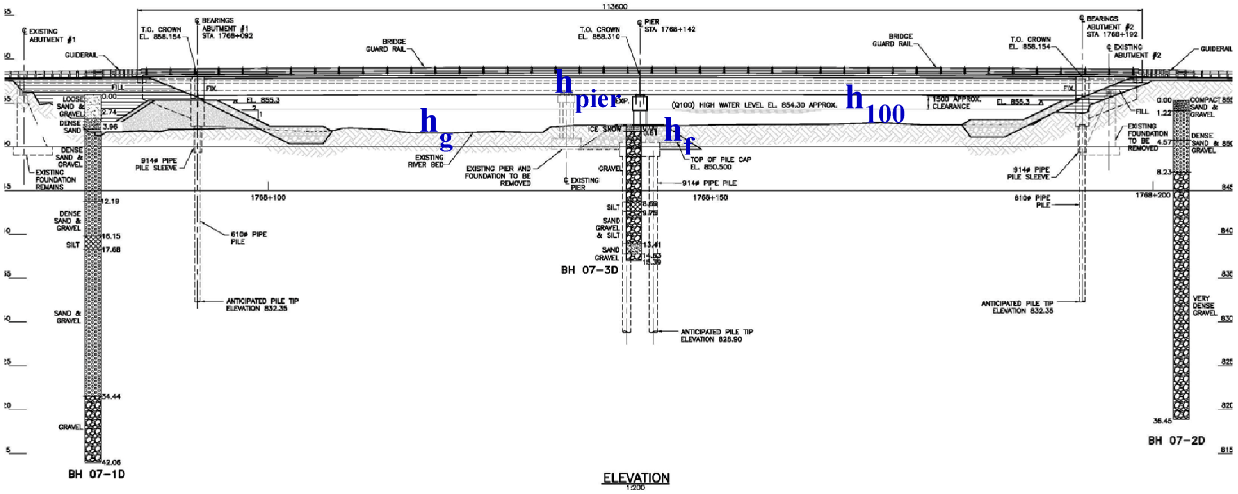


Fig. 3-5 Elevation View of Bridge #3 depicting the Parameters for Pier Scour Extreme Load Analysis

5. Formulate the hydrostatic pressure q acting (on the pier stem) at any point below the water level as a function of the height *h* of that point measured downward from the 100-year flood water elevation (h_{100}). For the calculation of the maximum pier scour moment, the height of interest is that measured from h_{100} water elevation to the top of pier footing ($h_{100} – h_f$) as this height represents the maximum column of water that loads the pier stem in bending. Further, the rationale for selecting the h_{100} elevation as the datum is that if the pier can resist the water forces at that elevation, it can resist those forces even better at lower elevations.

6. The height measured from h_{100} elevation to *riverbed elevation* h_g ($h_{100} – h_g$) is also important because it is when that height is exceeded that scour of foundation material starts. And that's the range of interest in terms of the bridge's vulnerability to pier scour: heights *h* from ($h_{100} – h_g$) to ($h_{100} – h_f$).

7. Formulate an expression for the bending moment M_q caused by the resultant of the hydrostatic pressure and calculated at the pier-to-footing joint.

8. By equating the available pier scour moment capacity M_{SCOUR} to the bending moment M_q caused by the resultant of the hydrostatic pressure, determine the height of water *h* that would result in the bending failure of the pier assuming that the bending resistance of the pier was based on the braking force load case.

9. If the height of water *h* is larger than the height from the 100-year flood water elevation to top of pier footing, namely, $(h_{100} - h_f)$, the pier bending capacity is larger than the bending moment caused by pier scour, which means that the pier is safe.

10. If, on the other hand, *h* is smaller than the height from the 100-year flood water elevation to top of pier footing, namely, $(h_{100} - h_f)$, the pier bending capacity is smaller than the moment caused by pier scour, which means that the pier is not safe. In that case, engineered apron would be recommended to protect the pier against scour.

3.5.2. Ice Accretion Extreme Load

a. Magnitude of Ice Accretion producing Failure of a through-Truss Bridge

The following steps are required for determining the magnitude of ice accretion that would produce the failure of a truss bridge (Fig. 3-4).

1. Identify the *most stressed* truss member (Member M_{ms}) for the load case in which all exposed truss members are subjected to a uniformly distributed ice accretion load of 1 kN/m length (q_1 = 1 kN/m), and denote the axial force in this member as F_1.
2. Calculate the un-factored truck live load axial force F_{ms} in Member M_{ms}
3. Assume the available ice-accretion load capacity for the most stressed member to be 70% of the un-factored live load axial force F_{ms}, and denote this force by F_{ice}.
4. Based on the magnitude of axial force F_1 caused by the unit ice accretion load as well as the magnitude of the available ice-accretion axial force capacity F_{ice}, determine the intensity of ice accretion load q_{ice} corresponding to the ice-accretion axial force capacity for the steel truss.

5. Using the unit weight of ice (γ_{ice}), convert the intensity of distributed ice accretion load (q_{ice}) into the thickness of accreted ice (t_{ice}) that would cause the collapse of the truss.
6. If the calculated thickness of accreted ice (t_{ice}) is rather large, the conclusion would be that the bridge is safe against ice accretion extreme loading. The basis for the said conclusion would be that such a large magnitude of ice accretion is unlikely, or the length of time it takes to accumulate that much ice avails the transportation agency and the public sufficient warning.
7. On the other hand, if the calculated (required) thickness of accreted ice is small, then the transportation agency would probably determine that the bridge is sensitive to ice accretion load, and that the bridge merits their attention and action.

3.6. Multi-Criteria Ranking of Competing Bridge Projects

3.6.1. Introduction

Based on literature, multi-criteria optimization of competing bridge projects is still an unresolved problem in Bridge Management. Often, optimization and prioritization are used interchangeably in published work on transportation and infrastructure management, whereas the two concepts are not one and the same at all. But if in both cases of prioritization and optimization, the projects are ranked in a top-to-bottom order, what then differentiates the multi-criteria prioritized list of projects from the multi-criteria optimized list of projects? The difference is in the formulation of the value function, in particular, the formulation of the criteria weights.

In the Analytic Hierarchy Process (AHP), for example, the criteria weights are constant from project to project so that only projects that rate high on large-weighted criteria attain high values. On the other hand, projects that rate high on low-weighted criteria attain low values of the prioritization function. This automatically leads to the trade-off of one important criterion in order to retain another important criterion. Giving up one desirable criterion in order to have another desirable criterion cannot be the goal of optimization.

In contrast, the method being contemplated will comprise *weights* derived from the rating of the bridges on each proposed criterion. The proposed method is demonstrated using the following four criteria: bridge performance, utility, vulnerability to climate-triggered extreme events, and vulnerability to climate-triggered extreme loads. It should be noted here that *bridge performance* (also known as *bridge condition index BCI* or *bridge sufficiency rating BSR*) is the primary objective measure used by most transportation agencies for bridge rating and, in this study, it is deemed to include the structural and operational safety and functionality of a bridge.

3.6.2. Criteria Weights

The formulation of criteria weights as proposed in this thesis allows the transportation agency to retain all desirable criteria in the selection of bridge projects under budget constraint. To this end, one of the major innovations in this thesis is the formulation of the criteria weight to include only those criteria that are individually considered important enough to govern the decision to program a bridge project ahead of other bridge projects slated for implementation. The other half of the weight formulation innovation is that, unlike previous approaches where the criteria are directly ranked, here it is the bridge projects (the alternative strategies) that are ranked on the basis of their performance (rating) on a given criterion relative to the other projects. Finally, the formulation allows the weight for each criterion to vary from project to project as opposed to remaining constant across projects as is the case with weights determined using the Analytic Hierarchy Process (AHP). The result is that, with the new method, if a bridge scores high on a criterion, then it automatically attracts a large weight for that criterion. The corollary is that projects attract low weights only on those criteria in which the bridge rates low.

The formulation of Eqn. (3-6) is proposed for criterion weight calculation to permit all criteria to be simultaneously accounted for in the multi-criteria ranking.

$$W(x) = (\gamma\lambda)_i / \sum_{i=1}^{i=n} \gamma_i \lambda_i \, (x) \tag{3-6}$$

In Eqn. (3-6):

W is the weight calculated for each optimization criterion x_1 to x_n;

γ is the weight parameter related to the ranking of the bridge on the criterion under consideration; and

λ = the bridge’s score (maximum = 100%) on the criterion under consideration.

Here, each ranking criterion, x_1 to x_n are selected on the basis that they are each important enough to govern the decision to program a bridge project ahead of other bridge projects slated for implementation. This requirement permits the weight for any one criterion to be as large as the bridge's ranking on that criterion dictates. For the weight parameter, γ, the said ranking is relative to all the other bridges selected for programming. The score for this weight parameter is calculated as γ = (N – Rank)/N. For example, if a bridge ranks 3rd out of 20 bridges on a criterion, the score is (20 – 3)/20 = 85%. If, instead, there are 30 bridges to be ranked, and the bridge ranks 3rd, the score is (30 – 3)/30 = 90.

On the other hand, the weight for the bridge's score λ tracks the actual performance of the bridge on the criterion, and it is necessary to track it because a bridge may rank 2nd out of 125 bridges while scoring only 45% and it could also rank 2nd out of 125 while scoring an impressive 94%.

Being objectively-determined, these weights should not be mistaken for the pre-determined/fixed weights that are assigned to the various criteria in a ***Bridge Sufficiency Rating*** calculation for example (Department of Highways & Public Works of Yukon 2010). The weights proposed in the present thesis vary from criterion to criterion and from bridge project to bridge project as the factors on which they depend vary from project to project.

This approach enables the elimination of preferential treatment of some criteria, and by so doing ensures that the totality of selected projects provides a mix of projects that capture all the desirables: prevention of sudden collapse caused by extreme loads and extreme events, early implementation of projects attracting the most benefits for tax payers, and promotion of projects that yield the most improvement in bridge performance per dollar of bridge preservation spending.

3.6.3. Characteristics of the Proposed Method

The philosophy of a direct multi-criteria ranking of competing bridge projects should be the following: a means to resolve a stalemate, namely, for two competing bridge projects that are to be ranked based on three criteria, the selected project will be the one that comes in equal with the other project on two of the three criteria, but tops the other project on the 3rd criterion. In this connection, it should be noted that Bridge "A" with a very high *performance* rating will not be overtaken by Bridge "B" with a very high *vulnerability to climate-triggered extreme event* rating if Bridge "A" does not score lower on *vulnerability to climate-triggered extreme event* rating than Bridge "B" scores on *bridge performance*.

It is clear that the fastest algorithm for multi-criteria ranking of competing bridge projects will be one that is a one-direction process, without any need to test a condition that might lead to a repetition of the computation cycles in order to arrive at an answer. It is also clear that the best result would be achieved if all the criteria are applied simultaneously in evaluating each project, rather than have a multi-stage evaluation in which one criterion is used for "screening" or "short-listing" the alternatives, and another criterion applied only to those projects that passed the screening test. That's because a project may score relatively low on one criterion but rather very high on another, and if it were screened out based on one criterion, it wouldn't even be around to show its advantage on the other criterion.

Further, if a project has a different score against each criterion, and if each criterion is important as industry experts have held (Thompson et al. 2008, Ellis et al. 2008, Thompson et al. 2003, Markow 2008, Mach and Hartman 2008, and Hajdin 2008), it would be better if it is ensured that all the criteria are simultaneously relied upon for ranking the projects. The above premise underscores the proposed method, which is described below.

For the calculation of the benefit to the agency (utility) accruing from the order of implementation of the projects, the present research has adopted the method of benefit calculation as employed in the *Ontario Bridge Management System OBMS* (Thompson et al. 2003), namely, the difference in the estimated bid price between implementing a project now rather than later. The premise is that further deterioration of the bridge will ensure that it will cost the agency or the tax payers more to implement a project 10 years later than it will cost to implement it now.

As will be shown in Chapter 6, the method is straight-forward and can handle any size of inventory, including the 50,000-bridge Texas DOT inventory. This is possible because each ranking criterion is handled separately in its own *spreadsheet* column, and the scores for each project, under the various criteria, are then combined by *simple summation*.

3.6.4 Steps for Implementing the Proposed Method

The following describes the steps required for implementing the proposed method for program-level ranking of bridge projects.

Step 1: Assume that the estimated total bid price for all the projects identified for implementation during the current programming period exceeds the available budget.

Step 2: Determine Bridge Rating against each ranking criterion based on the following steps.

(a) For each bridge that requires intervention, calculate the new Bridge Condition Index (BCI) following the proposed intervention scheme. Then, calculate the difference between the new and the old BCI. This represents the *improvement in performance* (δ_{BCI}) thanks to the money spent on the intervention. Then, calculate the *BCI Ratio* (δ_{BCI}/\$100,000) to represent the improvement in performance per \$100,000 of estimated project bid price (Table 3-11, Col 6).

It should be noted that different transportation agencies have different formulae for calculating the BCI or bridge performance or bridge sufficiency rating (BSR). In Yukon, for example, the bridge sufficiency rating (max 100%) is calculated using the following additive function with fixed weights: Structural Condition 35% + Load Rating 20% + Operational and Safety 45% (Yukon Government 2010). It should be noted that bridges rate higher on bridge performance after an intervention than before it receives intervention. It should also be noted that Transportation Agencies keep records and data on bridge performance for each bridge in the inventory.

(b) For each of the bridges featuring projects in Step (a) above, calculate the agency benefit per dollar of project cost of each alternative project by subtracting the present value of the long-term cost of the project from the present value of the long-term cost of the Do-Nothing alternative, then divide the difference by the cost of the project alternative being evaluated.

(c) <u>BCI/Cost Rating:</u> Award a score of 100% to the project with the highest BCI Ratio, and prorate the percentage BCI Ratio score of all other projects (Table 3-12, Column 7). The immediate advantage is that, at a glance, one can see the relative strengths of all the projects but without the need to perform any calculation. These will be designated as *equalized BCI Ratios*.

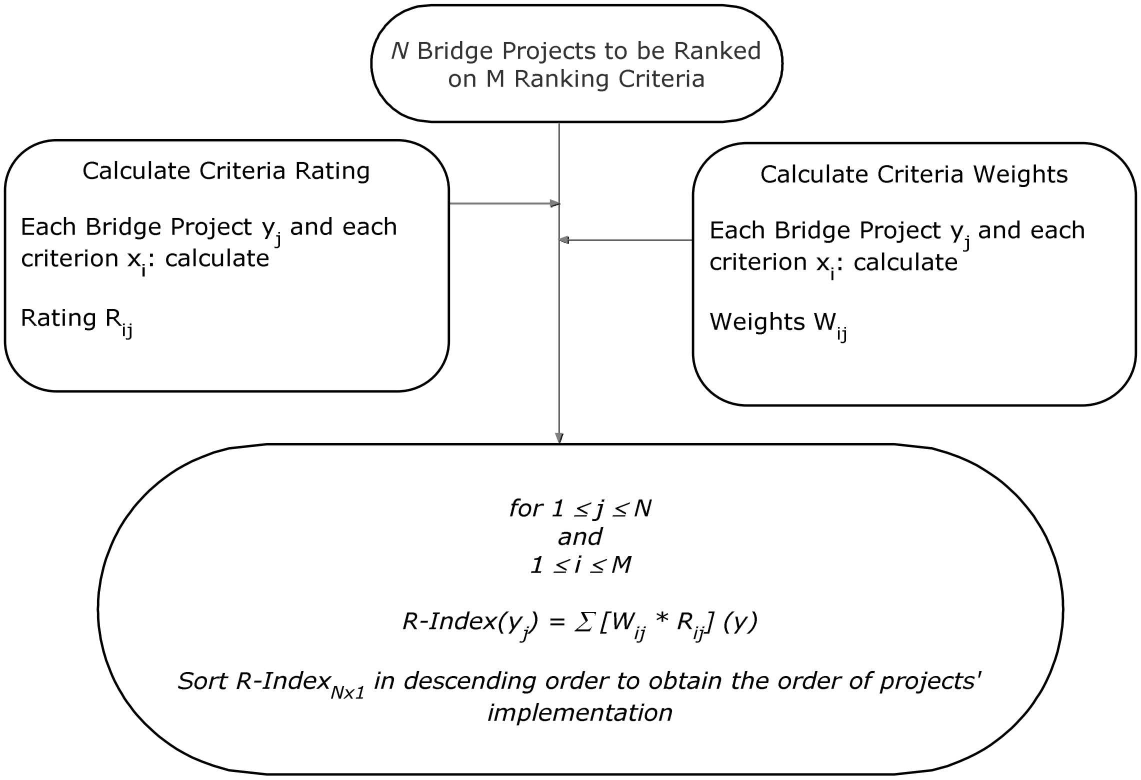


Fig. 3-6 Flow Chart – Direct, Non-Iterative, Multi-Criteria Ranking of Competing Bridge Projects

(d) Benefits/Cost Rating: Similarly, award a score of 100% to the project with the highest *Benefits Ratio* [Benefits/Cost Ratio], and prorate the Benefits Ratio percentage score of all other projects (Table 3-12, Column 9). These will be designated as *equalized Benefits Ratios* or utility.

(e) Climate-triggered Extreme *Event* Vulnerability Rating: This criterion is calculated as described earlier in Section 3.4.

(f) Climate-triggered Extreme *Load* Vulnerability Rating: This criterion is calculated as described earlier in Section 3.5.

(g) Determine the Ranking Index (*R-Index*) for each bridge as summation – over all the criteria – of the product of the *Weight* of each criterion and the *Rating* of the bridge on that criterion as depicted in Equation (3-7).

$$R - Index(W, R) = \sum_{i=1}^{i=m} W(x_i)R(x_i) \tag{3-7}$$

Table 3-11

Bridge Condition and Agency Benefits Indices

Bridge 1	New BCI 2	Old BCI 3	Benefits [$] 4	Cost [$][¥] 5	δ_{BCI}/Cost[¥¥] 6	Benefits/ Cost 7
Bridge #1	87.50	48.47	3,752,884	5,003,800	0.78	0.75
Bridge #2	90.03	51.46	3,109,803	3,494,000	1.10	0.89
Bridge #3	69.35	51.5	498,000	600,000	2.98	0.83
Bridge #4	71.32	53.5	462,000	600,000	2.97	0.77
Bridge #5	74.95	54.9	2,070,000	1,800,000	1.11	1.15
Bridge #6	90.03	64.9	763600	830,000	3.03	0.92
Bridge #7	69.93	49	8,549,000	8,300,000	0.25	1.03
Bridge #8	74.57	51	1,794,000	2,600,000	0.91	0.69
Bridge #9	88.72	55.13	896,970	1,031,000	3.26	0.87
Bridge #10	86.41	52.76	603,710	827,000	4.07	0.73
Total Cost				25,085,800		

[¥] Bridge Rehabilitation Cost

[¥¥] BCI Improvement per $100,000 spent on rehabilitation

The other half of the ranking function is the criteria rating, and those are presented in Equations (3-8) to (3-11).

Bridge Performance: $\zeta = 100\{\alpha_i / \alpha_{max} \mid 1 \le i \le N\}$ (3-8)

Utility: $\chi = 100\{\eta_i / \eta_{max} \mid 1 \le i \le N\}$ (3-9)

Extreme Events Vulnerability: $\tau = 100 - Resilience\,\%$ (3-10)

Extreme Loads Vulnerability: $\Omega = \{\Omega_i = 0 \text{ (Pass) or } 100 \text{ (Fail)} \mid 1 \le i \le N\}$ (3-11)

The expanded form of the ranking function can then be stated as:

$$R\text{-}Index(x_i) = \Sigma\{W_{\zeta i} * \zeta_i,\ W_{\chi i} * \chi_i,\ W_{\Omega i} * \Omega_i,\ W_{\tau i} * \tau_i(x) \mid 1 \le i \le N\} \quad (3\text{-}12)$$

In Equations (3-8) to (3-12), N is the number of projects to be programmed for implementation, α_i is the Bridge Performance Enhancement per \$100,000 cost of Project x_i, α_{max} is the maximum Bridge Performance Enhancement per \$100,000 cost of N Projects, η_i is the Utility per dollar cost of Project x_i, η_{max} is the maximum Utility per dollar cost of N Projects, Resilience % is the Bridge Resilience Indicator (BRI), and W_{ji} is the weight for Project y_j on Criterion x_i, $i = \zeta, \chi, \tau$

Table 3-12

Equalization of Bridge Condition and Agency Benefits Indices

Bridge	Year Built	Year Upgraded	Spans, Span Length (m)	Number of Lanes	BCI/Cost[¥] Ratio A	Converted BCI/Cost $100*A/A_{max}$ %	Benefit/Cost Ratio B	Converted Benefit/Cost $100*B/B_{max}$ %
1	2	3	4	5	6	7	8	9
Bridge #1	1968	2010	7 (290)	2	0.78	19.3	0.75	65.0
Bridge #2	1963	2009	4 (75)	2	1.10	27.1	0.89	77.4
Bridge #3	1947	2005	1 (61.2)	2	2.98	73.1	0.83	72.2
Bridge #4	1947	2005	1 (60.0)	2	2.97	73.0	0.77	67.0
Bridge #5	1946	2006	3 (89.4)	2	1.11	27.4	1.15	100.0
Bridge #6	1963	2006	1 (21.3)	2	3.03	74.4	0.92	80.0
Bridge #7	1944	2006	10 (445.9)	2	0.25	6.2	1.03	89.6
Bridge #8	1955	2008	2 (152.4)	2	0.91	22.3	0.69	60.0
Bridge #9	1943	2010	1 (18.8)	2	3.26	80.0	0.87	75.7
Bridge #10	1944	2010	1 (18.6)	2	4.07	100.0	0.73	63.5

[¥] Bridge Rehabilitation Cost

3.7. The Overall Model

The conception of the overall model for preservation management of highway bridges in the presence of climate-triggered extreme loads and climate-triggered extreme events is depicted in the Flow Chart of Fig. 3-7. While the model will be fully implemented in Chapters 4,

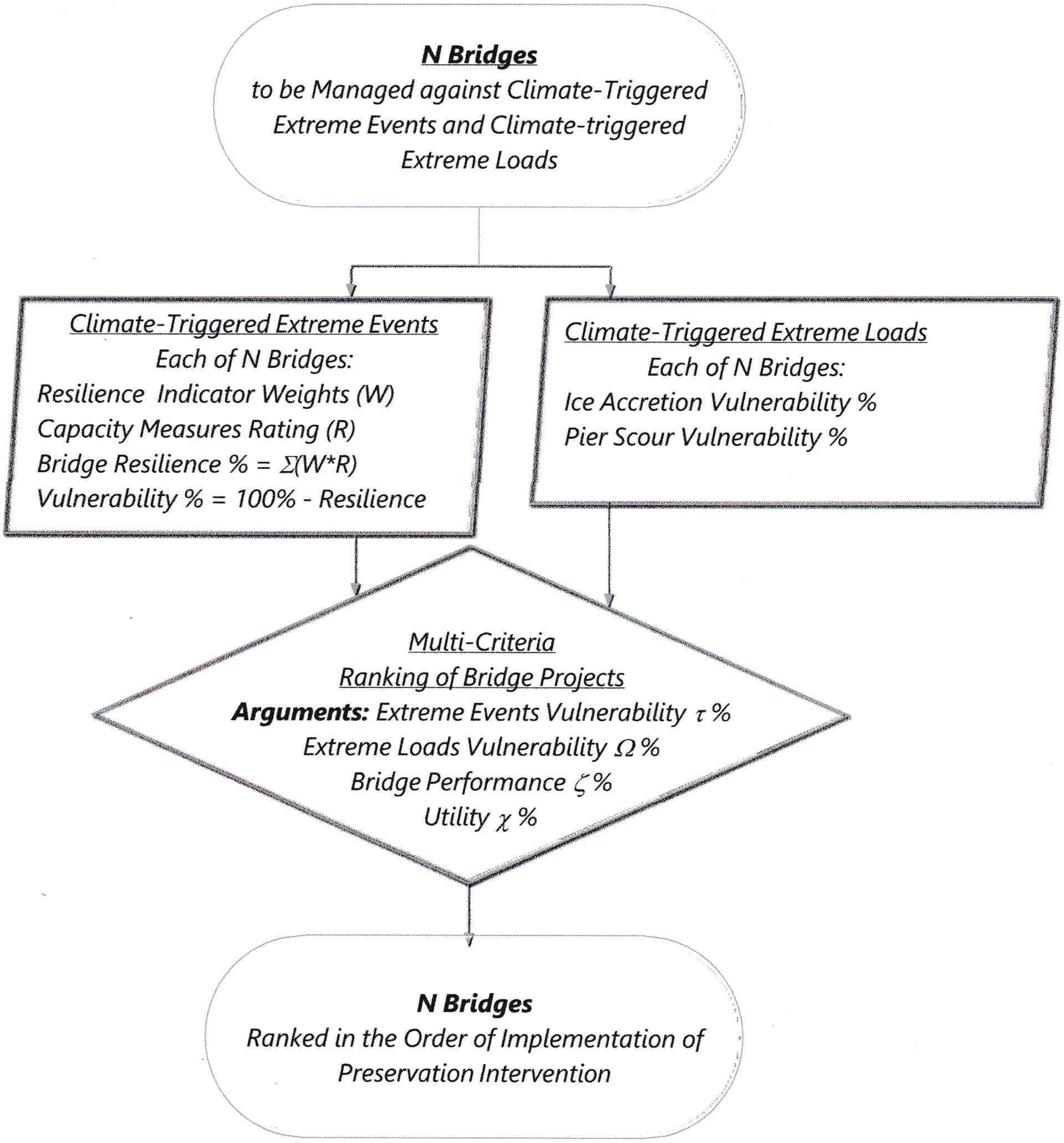


Fig. 3-7 Flow Chart – Managing Highway Bridges against Time-dependent Deterioration and Climate-Triggered Extreme Events/Loads

5, and 6, and although bridge performance and utility are not elaborated in the figure, it is important to note that Fig. 3-7 shows that each of the 4 criteria included in the ranking formulation are calculated separately and the ranking formulation is ultimately an aggregating function. Figure 3-7 shows that the proposed management model for highway bridges in cold regions should comprise the bridges' rating on each of the four criteria of climate-triggered extreme events vulnerability, climate-triggered extreme loads vulnerability, bridge performance, and utility.

3.8. The Analytic Hierarchy Process (AHP)

3.8.1 General

To contextualize the performance of the new ranking method proposed in this thesis, weights obtained using the Analytic Hierarchy Process (AHP) will be investigated in Chapter 7. For this purpose, data was collected via questionnaire distributed to 16 experts, from which 7 responses were received representing a 44% return rate. The pie chart of Fig. 3-8 shows the distribution of respondents: bridge code committee members (2), provincial chief bridge engineers (2), and both bridge code committee members and provincial chief bridge engineers (3). It should be noted that the sample population is very limited since there are only 10 provinces in Canada, which means there are only 10 provincial chief bridge engineers. Further, while there are about 20 members of the Technical Committee of the Canadian Highway Bridge Design Code, there are fewer than 10 members that practice bridge management. Considering this, although the sample size of 16 appears small, it is reasonable. Similarly, the 44% return rate will be shown in Chapter 7 to have no effect on the conclusions reached in the study since a full spectrum of weight schedules will be investigated rather than restricting the investigation to the one weight schedule derived from the questionnaire responses.

The four criteria which level of importance the survey respondents were asked to score were:

1. Bridge Performance (Bridge Condition Index, or BCI)
2. Utility (Cost Savings per dollar cost of intervention)
3. Climate-triggered Extreme Event Vulnerability
4. Climate-triggered Extreme Load Vulnerability

For the avoidance of doubt, the following definitions/descriptions of the criteria were issued to the survey respondents.

Bridge Performance (Bridge Condition Index, or BCI)

Over time, bridges deteriorate in physical/structural condition and the *bridge condition index (bridge performance)* plummets, thus necessitating preservation intervention. If intervention is applied, the bridge condition index jumps back up. When the bridge performance of one bridge improves, the re-calculated overall inventory bridge performance increases. From the standpoint of the entire inventory, a bridge that attains a high or very high increase in performance following intervention adds great value to the inventory.

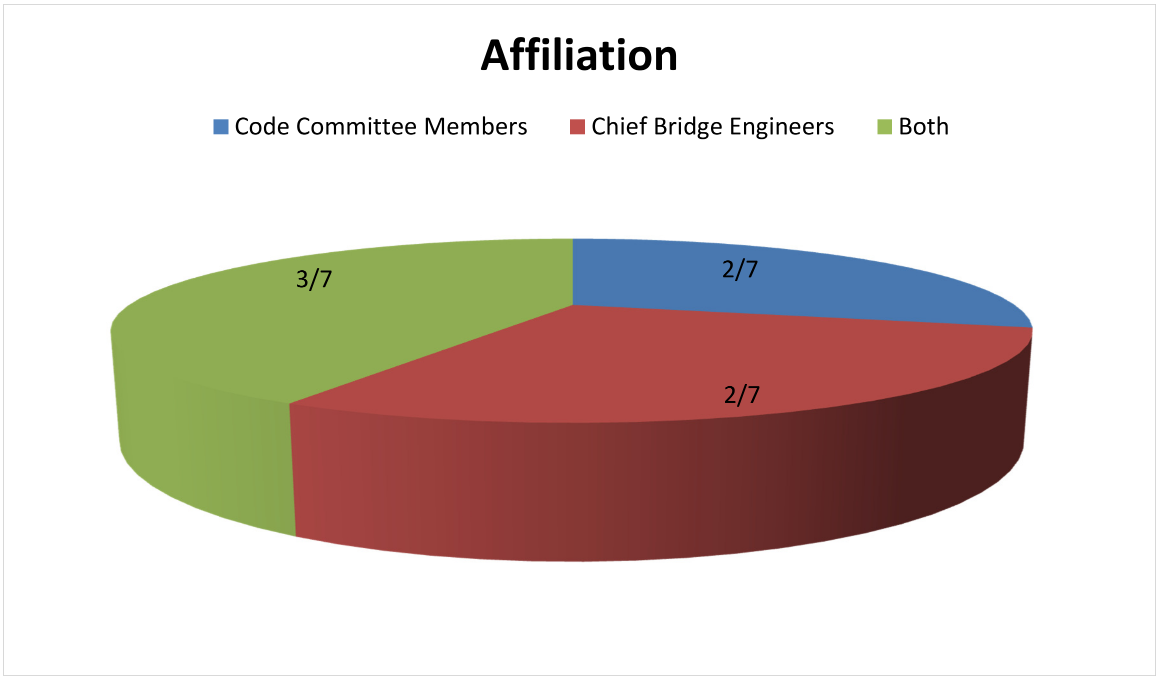


Fig. 3-8 Categories of Expertise of the Questionnaire Respondents

Utility (Cost Savings per dollar cost of intervention)

Utility (or, agency benefit) is calculated as the difference between the present value of the long-term cost of the project and the present value of the long-term cost of the Do-Nothing alternative, divided by the cost of the project. The premise is that further deterioration of the bridge will ensure that it will cost the agency or the tax payers more to implement a project 10 years later than it will cost to implement it now. Utility tracking allows the agency to minimize the *total life-cycle cost* of all the bridges in the inventory.

Climate-triggered Extreme Event Vulnerability

A bridge that has adequate resistance to truck live loads can still be vulnerable to climate-triggered extreme events. Extreme events such as abutment washout and melting permafrost instability can each produce sudden bridge failure while deck flooding can cause extensive damage to the bridge. Further, it could cost up to 10 times to rebuild a failed bridge what it would cost to retrofit the same bridge and thus prevent its failure.

Climate-triggered Extreme Load Vulnerability

Extreme loads such as pier scour or ice accretion can produce bridge failure in the presence of nominal levels of truck live loads. Structural analysis of a bridge will predict whether the bridge is susceptible to such loads, and the findings should be treated with the utmost importance.

3.8.2 Questionnaire Design

A total of 6 questions were posed in the survey to elicit pair-wise comparisons of the four criteria for the selection/programming of competing bridge projects. The following is a sample of the questions posed.

1. On a scale from *"Not at all Important"* to *"Extremely Important"*, please rate the importance of "bridge performance" relative to "utility" as a criterion for the selection/programming of bridges for intervention. By importance, we mean how positively or negatively you think or feel about a criterion relative to the other. The more positively you regard a criterion, the higher you would rate it. The more negatively you regard a criterion, the lower you would rate it.
2. On a scale from "Not at all Important" to "Extremely Important", please rate the importance of "climate-triggered extreme events vulnerability" relative to "climate-triggered extreme loads vulnerability" as a criterion for the selection/programming of bridges for intervention. By importance, we mean how positively or negatively you think or feel about a criterion relative to the other. The more positively you regard a criterion,

the higher you would rate it. The more negatively you regard a criterion, the lower you would rate it.

3.8.3 Analysis for Criteria Weights

The pair-wise comparisons provided by the survey respondents were analysed and synthesised in this section. Table 3-13 shows the response by Respondent #5 as a sample, while Tables 3-14 to 3-16 show the conversion of the responses to criteria weights.

Table 3-13 Priority Matrix – Respondent #5

	Performance	Utility	Extreme Events	Extreme Loads
Performance	1	5	3	3
Utility	0.2	1	0.2	0.333333
Extreme Events	0.333333	5	1	1
Extreme Loads	0.333333	3	1	1
COL_SUM	1.866667	14	5.2	5.333333

Table 3-14 Normalized Priority Matrix

	Performance	Utility	Extreme Events	Extreme Loads	Weights/Priority Vector
Performance	0.535714	0.357143	0.576923	0.5625	0.508070055
Utility	0.107143	0.071429	0.038462	0.0625	0.069883242
Ext. Events	0.178571	0.357143	0.192308	0.1875	0.228880495
Ext. Loads	0.178571	0.214286	0.192308	0.1875	0.193166209
COL_SUM	1	1	1	1	1

Table 3-15 Consistency Check

Priority Matrix					Weights			
1	5	3	3	X	0.50807	=	2.123626	4.17979
0.2	1	0.2	0.333333		0.069883		0.281662	4.030467
0.333333	5	1	1		0.22888		0.94082	4.110528
0.333333	3	1	1		0.193166		0.801053	4.146963
								4.116937
							CR =	0.038979
							CI =	0.04331

CI < 0.1 ⇨ The pair-wise comparison is consistent

Table 3-16 Weight/Priority Vector – All Respondents

	Respondent #							Average Weight
	1	2	3	4	5	6	7	
Perf.	0.40625	0.062043	0.317235	0.317235	0.50807	0.441327	0.322917	0.339297
Utility	0.177083	0.37966	0.464205	0.464205	0.069883	0.288265	0.322917	0.30946
Ext. E	0.177083	0.178637	0.10928	0.10928	0.22888	0.090986	0.239583	0.161962
Ext. L	0.239583	0.37966	0.10928	0.10928	0.193166	0.179422	0.114583	0.189282
Totals	1	1	1	1	1	1	1	1.000000

The average criteria weights of Table 3-16 are the AHP criteria weights that would be carried forward to Chapter 7, where the performance of the AHP Prioritization would be compared to the Multi-Criteria Ranking Method proposed in this thesis. The said weights are:

Bridge Performance	0.339297
Utility	0.30946
Extreme Events Vulnerability	0.161962
Extreme Loads Vulnerability	0.189282

Fig. 3-9a Bridge #1 – Side View of Single-Lane Bailey

Fig. 3-9b Bridge #2 – with New Pier Cantilevers

Fig. 3-9c Bridge #3 (Before 2009 Replacement)

Fig. 3-9d Bridge #5

Fig. 3-9e Bridge #9

Fig. 3-9f Bridge #11

Fig. 3-9g Bridge #10

Fig. 3-9h Bridge #12 – Deck Replacement – One Lane at a Time

3.9. Summary

In this chapter was described the various methodologies developed for the study and creation of a model for the management of highway bridges against climate-triggered extreme events/loads in cold regions. The methodologies are underscored by objectivity and generality so that they could apply to different number of criteria, are adaptable to different climatic regions, and are applicable to other fields of study and disciplines. Dissimilar methodologies were required for building the sub-models for each of the four criteria on which the management model is built.

The extreme climate-triggered event methodology comprises *resilience indicator* (RI) *weights* and *capacity measures rating* for the calculation of the Bridge Resilience %, while the extreme climate-triggered load methodology is formulated as a decision criterion that is expressed as unrealistic/plausible extreme flood magnitude or unrealistic/plausible thickness of accreted ice on steel truss members. *Bridge performance* and *utility*, on the other hand, are traditional criteria that are combined with the two climate-related criteria to produce a comprehensive management model for the continuous preservation management of highway bridge inventories in cold regions such as the Canadian Arctic and Alaska.

Finally, the definition of key concepts such as *infrastructure resilience*, *vulnerability*, and *optimization* was presented, as was data collection for a comparative study of weights obtained using the Analytic Hierarchy Process (AHP).

Chapter 4

Resilience Rating of Highway Bridges against Climate-Triggered Extreme Events

4.1. Introduction

Given that all three Northern Territories and the Northern belt of most of the provinces of Canada lie within the permafrost zone (Canadian Standards Association 2010), a significant number of bridges in Canada are subject to the projected increase in temperature, rainfall and flooding, snowfall and ice accretion, as well as melting permafrost, which will accompany climate change. In Northwestern Ontario alone, there are potentially 260 bridges founded in or above melting permafrost (permanently frozen ground). In Yukon, there are another 129 highway bridges sitting on permafrost.

In this chapter, the new method earlier introduced in Chapter 3 is applied to the climate change resilience rating of highway bridges in an actual inventory in the *Canadian Arctic* (Yukon Territory, Canada). Specifically, the application of the new method, and the associated analysis, involve fourteen (14) highway bridges in Yukon.

The objectives of this chapter are to:

- Demonstrate the application of the method developed in Chapter 3 to the climate-triggered extreme event vulnerability rating of highway bridges in cold regions.
- Rate each bridge to be programmed on each relevant capacity measure and thereby obtain the rating of the fourteen bridges on each Resilience Indicator (RI)
- Determine the Weight of each RI for each bridge.
- Establish relationships between the RI’s and the Resilience rating of the bridges.
- Perform sensitivity analysis to determine how the bridge resilience responds to changes in the capacity measure rating.

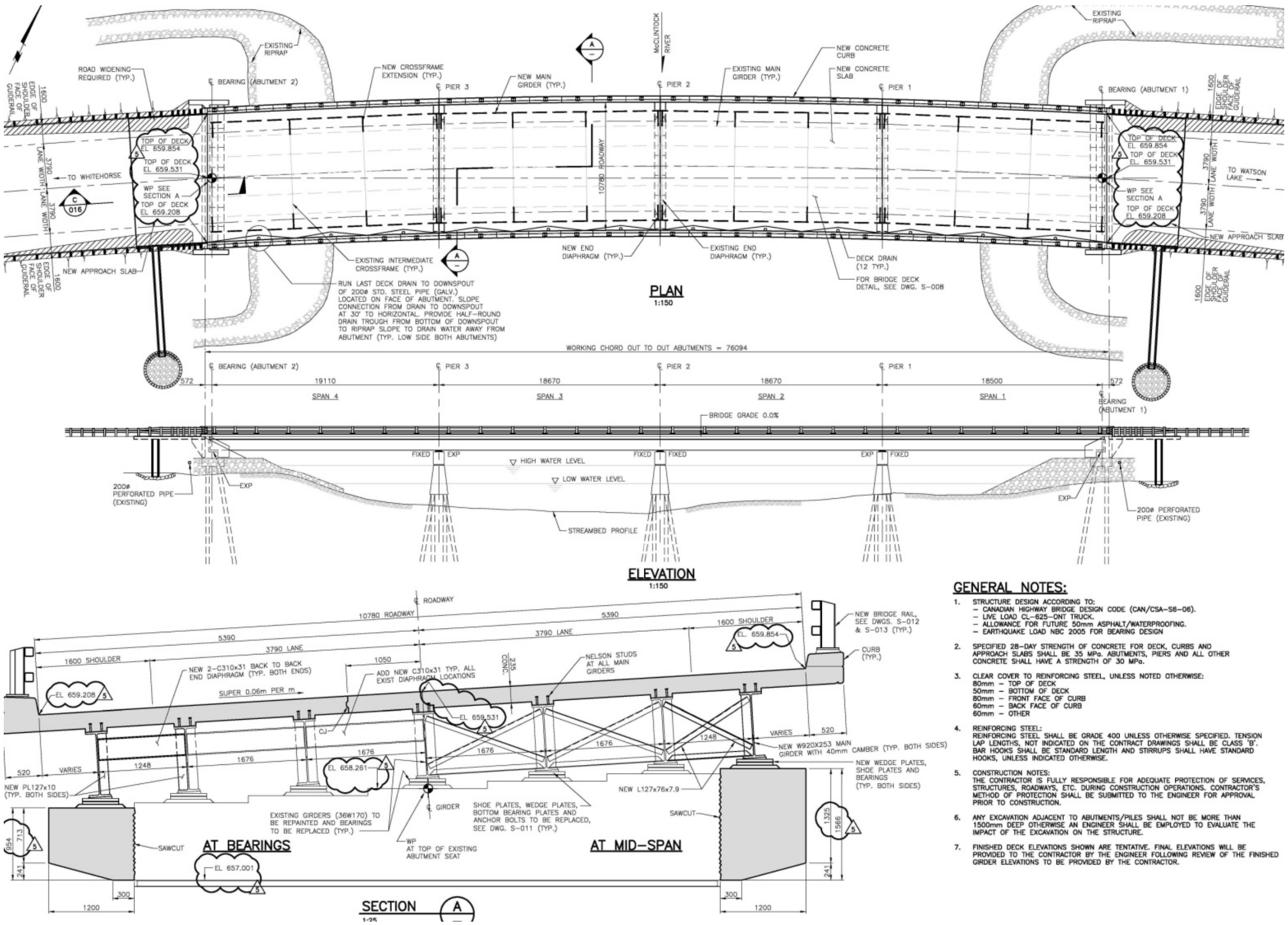
- Perform sensitivity analysis to determine how the bridge resilience responds to changes in the RI weights.
- Improve public awareness of climate change impacts on public transportation infrastructure.

4.2 Application of the Method

The application of the method is demonstrated using 14 bridges that have been identified for either a major rehabilitation or full replacement out of a total of 129 bridges in the transportation agency's inventory. Results are presented for all 14 bridges but only Bridges #1, #2, #3, and #4 are discussed in detail.

Figure 4-1 shows the plan, elevation and cross-section for Bridge #2, which is a 75 meters long bridge, with 4 spans each about 19 meters, built in 1963 and upgraded with a full deck replacement in 2009. Similarly, Figure 4-2 shows Bridge #4, which is a single span, 80 meters long, brand new steel plate-girder bridge, built in 2009 to replace a 2-span (2 x 61 m) through-truss bridge built in 1956. The RI weights for Bridges #2 and #4 were presented earlier in Tables 3-6 and 3-7, respectively. With respect to the Weights shown in the last column of both Tables, it should be noted that Bridge #2 is a multi-span bridge with piers while Bridge #4 is a single-span bridge with no pier.

Table 4-1a and Table 4-1b show the resilience indicator weight and the capacity measure rating, respectively, for 4 of the 14 bridges covered in this study, including Bridges #2 and #4 described above. The *Rating Scheme* of Table 3-8 was used for rating these and the other 10 bridges. In the case of the *Hydraulic Capacity* measure, the standard adopted for this study is the 1.5 meters freeboard as required by the *Canada Navigable Waters Protection Act* (Government of Canada 1985) for a 100-year flood. However, all 4 capacity measures are assessed against the demands of the extrapolated climate conditions of the last quarter of this century (2070's), which are



RUN LAST DECK DRAIN TO DOWNSPOUT OF 200ø STD. STEEL PIPE (GALV.) LOCATED ON FACE OF ABUTMENT. SLOPE CONNECTION FROM DRAIN TO DOWNSPOUT AT 30° TO HORIZONTAL. PROVIDE HALF-ROUND DRAIN TROUGH FROM BOTTOM OF DOWNSPOUT TO RIPRAP SLOPE TO DRAIN WATER AWAY FROM ABUTMENT (TYP. LOW SIDE BOTH ABUTMENTS)

GENERAL NOTES:

1. STRUCTURE DESIGN ACCORDING TO:
   - CANADIAN HIGHWAY BRIDGE DESIGN CODE (CAN/CSA-S6-06).
   - LIVE LOAD CL-625-ONT TRUCK.
   - ALLOWANCE FOR FUTURE 50mm ASPHALT/WATERPROOFING.
   - EARTHQUAKE LOAD NBC 2005 FOR BEARING DESIGN
2. SPECIFIED 28-DAY STRENGTH OF CONCRETE FOR DECK, CURBS AND APPROACH SLABS SHALL BE 35 MPa. ABUTMENTS, PIERS AND ALL OTHER CONCRETE SHALL HAVE A STRENGTH OF 30 MPa.
3. CLEAR COVER TO REINFORCING STEEL, UNLESS NOTED OTHERWISE:
   80mm – TOP OF DECK
   50mm – BOTTOM OF DECK
   80mm – FRONT FACE OF CURB
   60mm – BACK FACE OF CURB
   60mm – OTHER
4. REINFORCING STEEL:
   REINFORCING STEEL SHALL BE GRADE 400 UNLESS OTHERWISE SPECIFIED. TENSION LAP LENGTHS, NOT INDICATED ON THE CONTRACT DRAWINGS SHALL BE CLASS 'B'. BAR HOOKS SHALL BE STANDARD LENGTH AND STIRRUPS SHALL HAVE STANDARD HOOKS, UNLESS INDICATED OTHERWISE.
5. CONSTRUCTION NOTES:
   THE CONTRACTOR IS FULLY RESPONSIBLE FOR ADEQUATE PROTECTION OF SERVICES, STRUCTURES, ROADWAYS, ETC. DURING CONSTRUCTION OPERATIONS. CONTRACTOR'S METHOD OF PROTECTION SHALL BE SUBMITTED TO THE ENGINEER FOR APPROVAL PRIOR TO CONSTRUCTION.
6. ANY EXCAVATION ADJACENT TO ABUTMENTS/PILES SHALL NOT BE MORE THAN 1500mm DEEP OTHERWISE AN ENGINEER SHALL BE EMPLOYED TO EVALUATE THE IMPACT OF THE EXCAVATION ON THE STRUCTURE.
7. FINISHED DECK ELEVATIONS SHOWN ARE TENTATIVE. FINAL ELEVATIONS WILL BE PROVIDED TO THE CONTRACTOR BY THE ENGINEER FOLLOWING REVIEW OF THE FINISHED GIRDER ELEVATIONS TO BE PROVIDED BY THE CONTRACTOR.

Fig. 4-1 Bridge #2 – Plan, Elevation, & Section higher than today's demands (ACIA 2004). That means that for hydraulic capacity, the 14 bridges reported in this paper are assessed against 1.85 meters for the 2070's, being the sum of 1.5 meters and the projected sea level rise in the Canadian Arctic of 350 mm over the first 7 decades of this century.

With the weights and ratings established, the Resilience Indicator (RI) is calculated as the *product* of the *Weight %* and the ratio of the bridge *Rating* on the associated capacity measure, *divided* by the *maximum Rating* available. As an example of how the RI is calculated, the calculation of the RI for Pier Scour for Bridge #2 is detailed in the Flowchart of Fig. 3-2. Further, the BR results for Bridges #1 to #4 are presented in detail in Table 4-1c.

For these 4 bridges, the BR are calculated as the product of each column of the matrix $[\text{Ratings}]_{5x4}$ of Table 4-1b and the matching row of the matrix $[\text{Weights}]_{4x5}$ of Table 4-1a. The sum of the 5 indicators shown for each bridge in Table 4-1c is the Bridge Resilience Indicator for the respective bridges. Finally, the Bridge Resilience for the 14 bridges are shown in Table 4-2 (Column 2, *Climate Change Resilience Rating*).

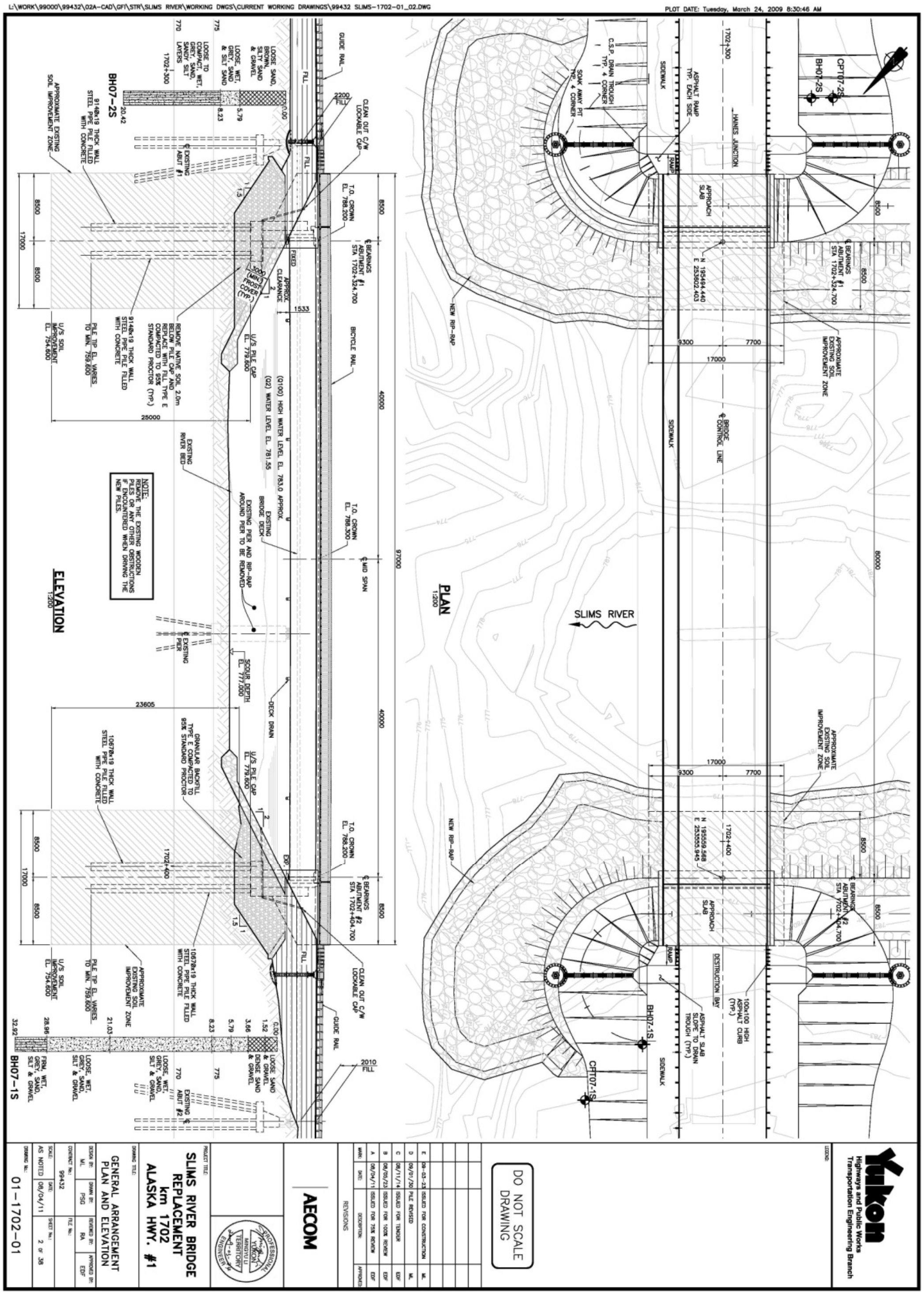


Fig. 4-2(a) Bridge #4 – Plan & Elevation

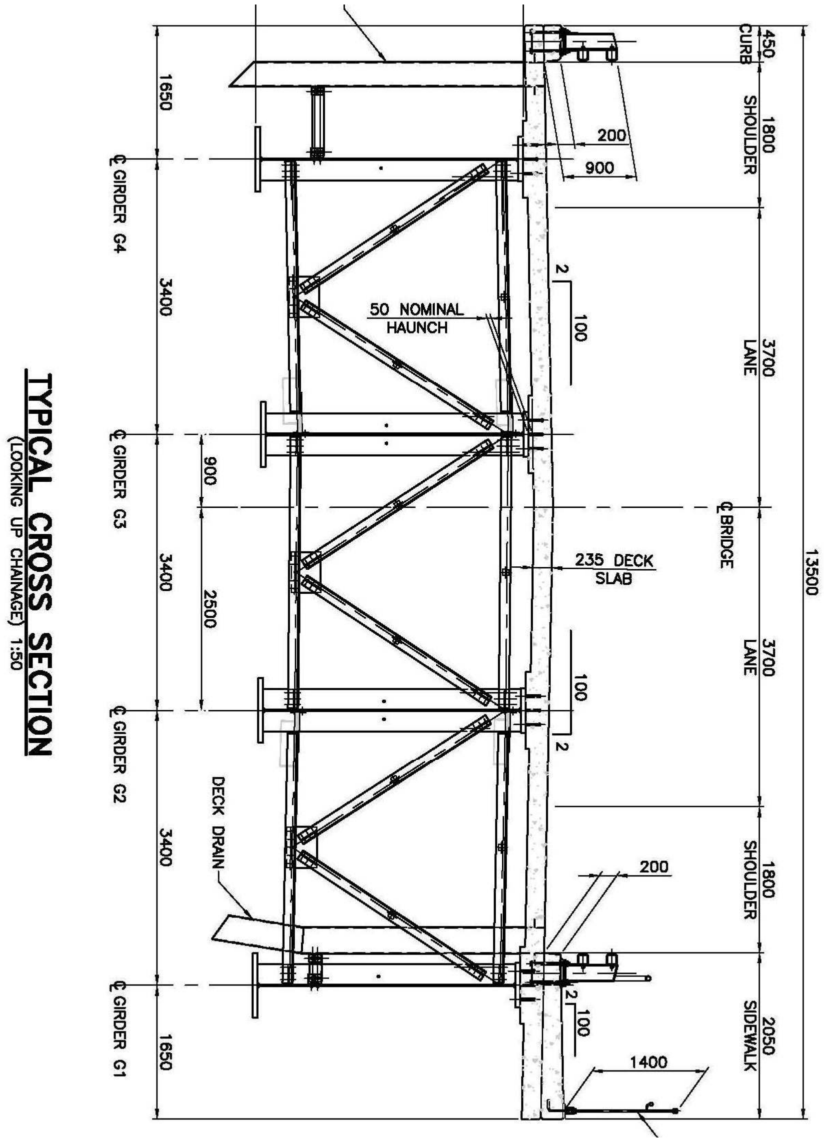


Fig. 4-2(b) Bridge #4 – Cross Section

4.3. Discussion of Results

Table 4-1c shows very high BR scores for Bridges #3 and #4, namely, 92.4% for Bridge #3 and 91.7% for Bridge #4. This is good, and it reflects the great amount of investment of effort and funding that went into the procurement of engineering services for the design of these two bridges.

Table 4-1a Matrix of Weights (%) for Bridges #1 to #4 $[\text{Weights}]_{4x5}$

	Abutment Washout	Pier Scour	Abutment Erosion	Deck Flooding	Abutment Permafrost
Bridge #1	70.85	0	8.5	12.15	8.5
Bridge #2	44.32	12.5	13.3	16.62	13.3
Bridge #3	64.94	8.35	7.79	11.13	7.79
Bridge #4	71.94	0	8.6	10.8	8.6

Table 4-1b Matrix of Capacity Measures' Rating for Bridges #1 to #4 $[\text{Ratings}]_{5x4}$

	Bridge #1	Bridge #2	Bridge #3	Bridge #4
Hydraulic Capacity	0/20	10/20	18/20	18/20
Pier Protection	–	12/15	15/15	–
Abutment Insulation and/or Piling	15/15	12/15	15/15	15/15
Hydraulic Capacity	0/20	10/20	18/20	18/20
Abutment Insulation and/or Piling	15/15	12/15	15/15	15/15

Table 4-1c Matrix of Resilience Indicators for Bridges #1 to #4

	Bridge #1	Bridge #2	Bridge #3	Bridge #4
Abutment Washout	0.0	22.2	58.4	64.8
Pier Scour	N/A	10.0	8.4	N/A
Abutment Erosion	8.5	10.6	7.8	8.6
Deck Flooding	0.0	8.3	10.0	9.7
Abutment Permafrost	8.5	10.6	7.8	8.6
Totals	17.0%	61.7%	92.4%	91.7%

Structural, hydro-technical, and geo-technical services were tendered in 3 separate calls for proposal, and the 3 successful proponents were each awarded the 2 bridges as a bundle.

The only reason that these bridges did not each score 100% for BR is because the hydraulic capacity was sized for the current requirement of 1.5 meters for the 100-year flood, and without any extra allowance for the 350 mm that represents the projected rise in sea level by the last quarter of this century. In comparison, the traditional Bridge Condition Index (BCI) score for each bridge is 94.56%.

On the other hand, Bridges #1 and #2 register low scores for BR at 17% and 61.7%, respectively. These compare unfavorably with their traditional BCI scores of 87.50% and 90.03%, respectively. It should be noted that Bridge #1 is a brand new bridge and Bridge #2 is a superbly and comprehensively rehabilitated bridge, so long as they are evaluated from the point of view of bridge condition only. Indeed, Bridge #1 was awarded a score of only 25% for channel adequacy in the Agency's calculation of the BCI.

Sometimes, "local politics" trumps engineering opinion in project design and delivery, as was the case with Bridge #1. On this project, the engineer, understanding that raising the bridge high enough to improve hydraulic capacity might flood a home located within 15 meters of the bridge, decided to go for only a 300 mm raise, but the home owner objected. The home owner did not want the bridge or the bridge approach to be raised at all. As a result, the engineer had to settle for only 150 mm raise. Meanwhile, the flood discharge of 2009 was exactly equal to the 100-year flood discharge flow rate of 225 m^3/s and the flood water level came within 100 mm (4 inches) of the soffit of the old bridge. So, assuming that during the next 100 years there would be no flood exceeding the 2009 flood, the bridge has a vertical clearance of 250 mm (100 mm existing freeboard + 150 mm improvement as per 2010 construction) and would safely pass such a flood. However, should the river rise by 350 mm as projected for the 2070's on account of climate change, the bridge would then be 100 mm under water.

There was the option of widening the channel given that the new bridge is 36.6 meters long as compared to the existing bridge length of 30.5 meters. However, excavating and removing material from the river banks would have attracted a rather lengthy process for acquiring environmental permits, and the option was not pursued. Therefore, as this bridge would be under water for the climate change scenario assumed for this study, Bridge #1 was rated 0 (zero) out of 20 for hydraulic capacity. In the case of Bridge #2, there was no attempt at all to raise the bridge soffit, notwithstanding that flood water in recent years had come very high near the bridge soffit.

Thus, although the above two bridges have very high BCI as a direct result of recent investment in replacement and a comprehensive rehabilitation, respectively, they could be significantly compromised in the event of a high magnitude flood discharge due to climate change effect that could have been contained without spending much money at all.

4.4. Climate Change Vulnerability Rating of Highway Bridges

4.4.1 General

Consider a transportation agency managing a highway bridge inventory of 157 bridges, of which 14 bridges have been earmarked for major rehabilitation. Further, the transportation agency wishes to optimize the order of implementation of the 14 projects on the basis of the 4 criteria of *vulnerability to climate-triggered extreme events*, *vulnerability to climate-triggered extreme loads*, *bridge performance*, and *utility*. This chapter is devoted to the bridges' rating on *vulnerability to climate-triggered extreme events* and Table 4-2 presents that rating for 14 bridges from a jurisdiction in the Canadian North. The rating of 4 of the 14 bridges has been presented earlier in detail in Tables 4-1a, 4-1b, and 4-1c.

Based on the Resilience rating for a bridge, the Vulnerability rating is calculated as:

$$\textit{Vulnerability Rating} = 100\% - \text{Resilience } \% \quad (4\text{-}1)$$

where:

Resilience % for each bridge is the Bridge Resilience calculated for each bridge and reported in Table 4-2 (Column 2).

Table 4-2

Climate Change Vulnerability Rating – 14 Bridges

Bridge 1	Climate Change Resilience Rating % 2	Climate Change Resilience Ranking 3	Climate Change Vulnerability Rating % 4	Climate Change Vulnerability Ranking 5
Bridge #1	17.0	14th	83.0	1st
Bridge #2	61.7	12th	38.3	3rd
Bridge #3	92.4	4th	7.6	11th
Bridge #4	91.7	5th	8.3	9th
Bridge #5	100.0	1st	0.0	14th
Bridge #6	91.7	5th	8.3	9th
Bridge #7	98.0	2nd	2.0	13th
Bridge #8	88.0	8th	12.0	6th
Bridge #9	94.7	3rd	5.3	12th
Bridge #10	71.9	11th	28.1	4th
Bridge #11	89.5	7th	10.5	8th
Bridge #12	88.0	8th	12.0	6th
Bridge #13	75.0	10th	25.0	5th
Bridge #14	46.6	13th	53.4	2nd

The *Vulnerability Rating* for all 14 bridges is shown in Table 4-2 (Column 4). The Table also shows the *Vulnerability Ranking* (Column 5) for the 14 bridges. Table 4-2 (Column 2) shows that a large majority of the ensemble of the 14 bridges have very high Resilience rating. The reason they have high resilience is because most of the bridges have excellent clearance above water and also because they are founded on steel piles, which serve to isolate the foundations of these structures from the warming and melting permafrost layers nearer to the ground surface. That is just as well because, except for Bridge #1, all of these bridges are on one major highway, which has no detour routes for over half of its 1000 km length, triggering the designation of all the bridges on the entire highway as *lifeline structures*. Therefore, the transportation agency cannot afford the consequences of these bridges failing.

Because they are highly resilient, the vulnerability of the 14 bridges is very low (Fig. 4-3), with only 15% (2 of 14) of the bridges scoring over 50% on the Vulnerability Scale and only 35% (5 of 14) scoring over 20%.

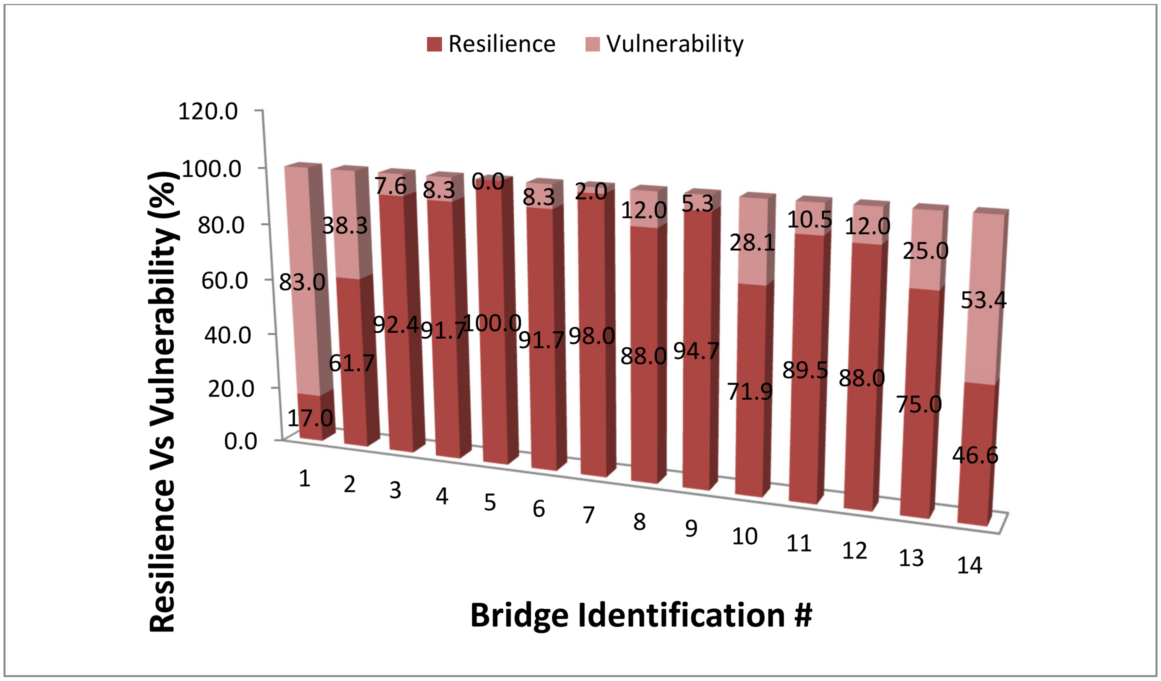


Fig. 4-3 Resilience Vs Vulnerability – 14 Highway Bridges in the Canadian North

4.4.2 Sensitivity of the Method

Users of the proposed method would like to know as much as possible about the performance of the method. For example, what is the effect of small or large changes in input (capacity measures rating, bridge resilience weights, etc.) on the resilience rating of a bridge? Does a small change in hydraulic capacity rating, for instance, result in a commensurate change in resilience rating of the bridge, or does a small change in hydraulic capacity lead to a disproportionately large change in the resilience rating of the bridge. To study this phenomenon, sensitivity analysis of changes in hydraulic capacity and detour availability of the bridges was undertaken as follows.

Suppose that Bridges #3, #4, and #5 have vertical clearances above water of 0.75 metre (previously, 1.7 m), 1 metre (previously 1.8 m), and 0.5 metre (previously 2.18 m), respectively. Further, suppose that those same bridges (Bridges #3, #4, and #5) are also located in a highway segment with detour routes of lengths 120 km, 70 km, and 235 km, respectively. How would each of these two scenarios affect the resilience ranking of these 3 bridges, on one hand, and the other 11 bridges, on the other hand? Finally, suppose also that the hydraulic capacity of the bottom 3 bridges (Bridges #2, #14 and #1) improved to 1.7 metres in each case, how would that change their resilience ranking and the resilience ranking of the other 11 bridges?

a. Hydraulic Capacity Sensitivity – Bridges #3, #4, and #5

For Scenario #1 in which Bridges #3, #4, and #5 have vertical clearances above water of 0.75 metre, 1 metre, and 0.5 metre, respectively (compared to the 2070's standard of 1.85 metres), the corresponding Hydraulic Capacity rating [see *Rating Guide* in Table 3-8] are 10.5/20 [Bridge #3], 14/20 [Bridge #4], and 7.5/20 [Bridge #5]. The effect of these 3 changes on the resilience rating of these 3 bridges are as follows: Bridge #3 falls from 92.4% to 63.9%, Bridge # 4 drops from 91.7% to 75.2%, and Bridge #5 falls from 100% Resilient to 54.9%. The contribution of each of the 5 resilience indicators to the Resilience of the 3 Bridges is depicted in Fig. 4-4(a) (Actual Inventory: denoted by 3, 4, and 5, versus Scenario #1: denoted by 3', 4', and 5'). For Bridge #3, Fig. 4-4(a) shows that the 2 resilience indicators affected by hydraulic capacity (abutment washout and deck flooding), plummet from 58.4 % and 10% to 34.1% and 5.8%, respectively. The other 3 resilience indicators remain unchanged. Further, it can be seen that the corresponding changes in Resilience Ranking are the following: Bridge #3 drops from 4th to 10th, Bridge #4 falls from 5th place to 7th place, and Bridge #5 falls steeply from 1st place to 12th. Therefore, the Method is able to capture the effects of changes in hydraulic capacity *scenario*.

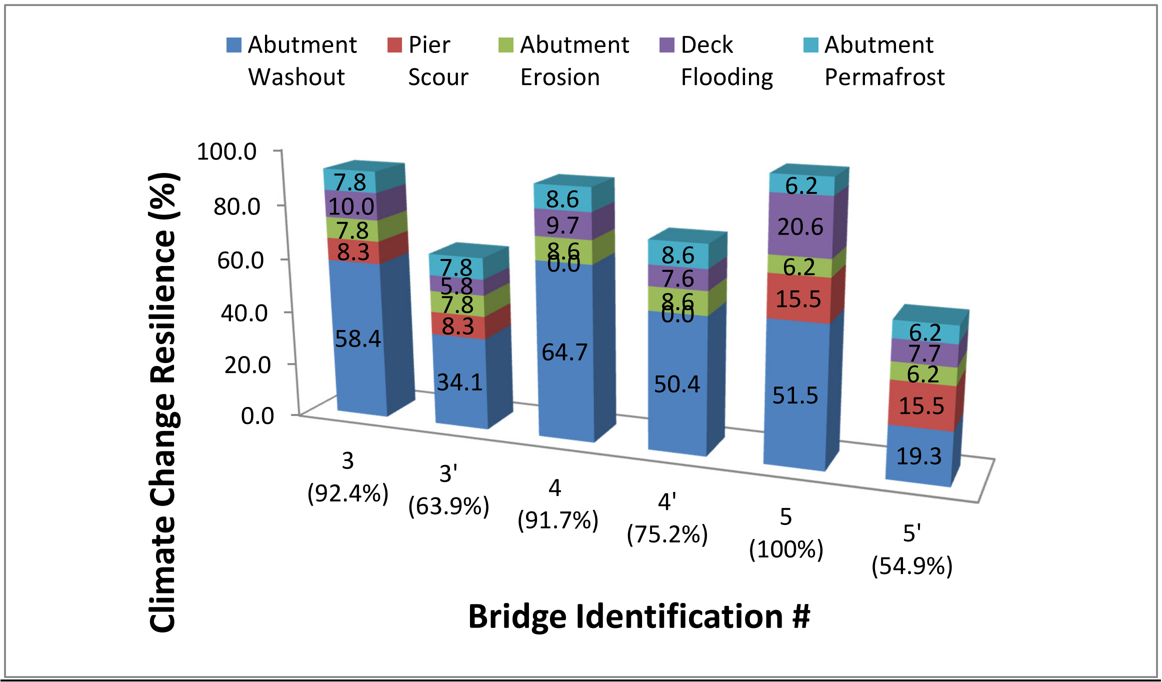
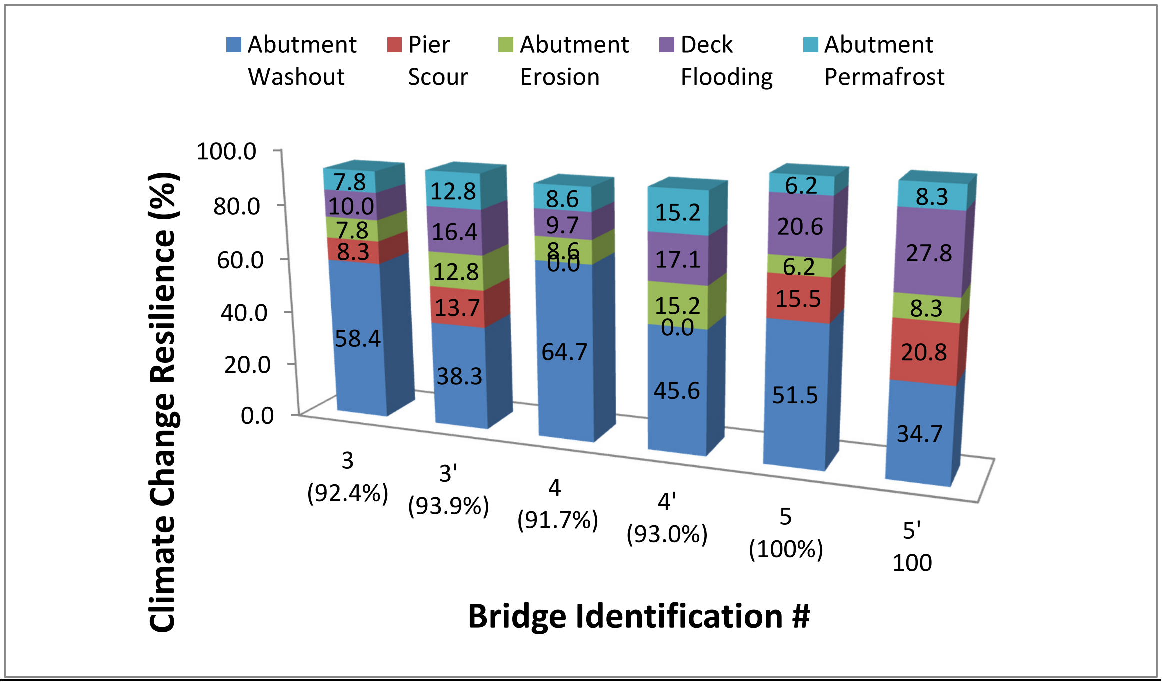


Fig. 4-4a Demonstration of Hydraulic Capacity Sensitivity – Bridges #3, #4, and #5

b. Detour Availability and Detour Length Sensitivity – Bridges #3, #4, and #5

For the second scenario (Scenario #2) in which Bridges #3, #4, and #5 go from having no detour routes at all to having detour routes of length 120 km (User Cost "Φ" = 2), 70 km (User Cost "Φ" = 2), and 235 km (User Cost "Φ" = 2.5), respectively, the corresponding effect on their bridge resilience indicators are as follows. Bridge #3 and Bridge #4 improve from 92.4% and 91.7% to 93.9% and 93.0%, respectively. It is not a big jump in rating, because their original ratings are already high at 92% and 91%, respectively. But the method must be able to capture



<u>Fig. 4-4b</u> Demonstration of Detour Sensitivity – Bridges #3, #4, and #5

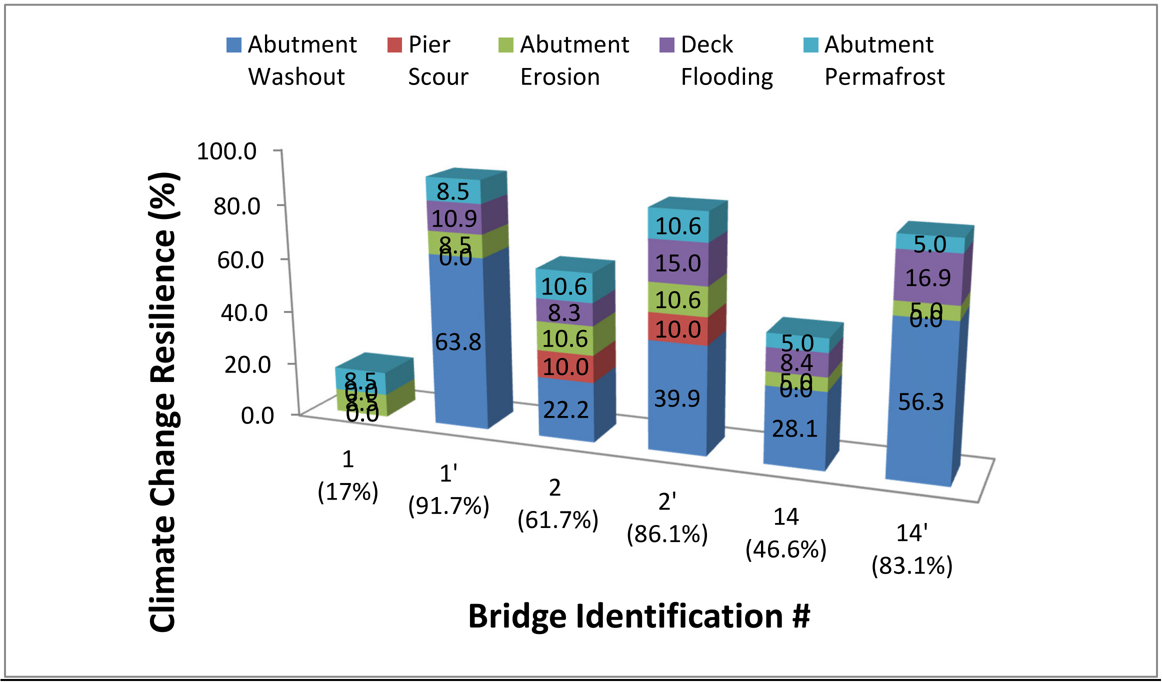
that improvement, and it is an improvement if detour routes are available so that the public is not trapped in the event of an emergency such as the unavailability of Bridges #3 and #4. Finally, notice the significant decrease in the abutment washout component of the BRI for Bridge #3 (Fig. 4-4b), which is now only 38.3 (down from 58.4). The decrease is due to a corresponding decrease in abutment washout *weight*. Recall that the more dire the consequences for the traveling public, the higher the weight attracted by the bridge resilience indicator. Now that there is 120 km long detour route associated with Bridge #3, the weight of the abutment washout resilience indicator decreases. However, the *rating* of the bridge on hydraulic capacity (18/20) does not change, so that the product of *weight* times *rating* (which determines the value of the abutment washout resilience indicator) decreases as shown in Fig. 4-4b. Since Bridge #3 rated at maximum on all capacity measures except *hydraulic capacity*, the overall BR score for Bridge #3 increases from 92.4% to 93.9% as three of the other resilience indicators (abutment erosion, pier scour, and abutment permafrost instability) now have higher weights than previous to go along with their maximum rating (15/15). The reason that the weights increase for the other resilience indicators is to compensate for the decrease in the weight of the abutment washout indicator, and that in turn is because the resilience indicators always must sum up to 100%.

Bridge #5, on the other hand, was already at 100% Resilience Rating and its rating could not be further improved. The rating remained at 100% before and after the detour-triggered weight changes. As noted earlier, the weights of the resilience indicators for each bridge must always sum up to 100%. The weights merely get redistributed and in the case where a bridge already rates at the maximum for all the corresponding capacity measures, the bridge resilience indicator will remain at 100% no matter the distribution of the weights. The 100% score can only be achieved when a bridge scores the maximum possible on all the relevant capacity measures, and that does not change when the weights change. To paint a complete picture, it should also be noted that changes in detour availability only affect the resilience indicator *Weights* and not the capacity measure *Ratings* of the bridge. Finally, notice the changes in the values of the component resilient indicators (Fig.4-4b), which nonetheless produce no change in the total bridge resilience indicator for Bridge #5 (100% for no-detour and 100% for 230 km detour).

c. Hydraulic Capacity Sensitivity – Bridges #2, #14, and #1

The effects of improving the freeboard (hydraulic capacity) of the bottom-ranked Bridges #2, #14, and #1 to 1.7 metres each (previously 0.7metre, 0.638 metre, and – 0.1 metre, respectively) would be as follows. As shown in Figure 4-4c, the resilience of the three bridges improves significantly. Bridge #1 improves from 17% to 91.7%, Bridge #2 improves from 61.7% to 86.1%, and Bridge #14 improves from 46.6% to 83.1%. These results show that improving the hydraulic capacity of Bridge #1 from – 0.1 metre to 1.7 metres (97% improvement with reference to the standard freeboard of 1.85 metres) improves the bridge's resilience from 17% to 91.7%. In the case of Bridge #2, 54% improvement in hydraulic capacity rating leads to a new resilience rating of 86.1%, a 24.4% improvement in resilience. Finally, for Bridge #14, 57% improvement in hydraulic capacity rating leads to 36.5% improvement in resilience rating. Based on these metrics, it could be concluded that significant changes in bridge hydraulic capacity leads to commensurate and significant changes in bridge resilience in the same direction. This in turn means that the method is sensitive to hydraulic capacity changes, but not hypersensitive.

The changes to the ranking of these 3 bridges, and the other 11 bridges, are shown in Table 4-3 (Column 9).



<u>Fig. 4-4c</u> Demonstration of Hydraulic Capacity Sensitivity – Bridges #1, #2, and #14

Table 4-3

Hydraulic Capacity and Detour Availability Sensitivity

Bridge	Climate Change Resilience Rating		Scenario #1		Scenario #2		Scenario #3	
		Rank	%	Rank	%	Rank	%	Rank
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Bridge #5	100	**1st**	54.9	**12th**	100	**1st**	100	1st
Bridge #7	98	2nd	98	1st	98	2nd	98	2nd
Bridge #9	94.7	3rd	94.7	2nd	94.7	3rd	94.7	3rd
Bridge #3	92.4	**4th**	63.9	**10th**	93.9	**4th**	92.4	4th
Bridge #4	91.7	**5th**	75.2	**7th**	93.0	**5th**	91.7	5th
Bridge #6	91.7	6th	91.7	3rd	91.7	6th	91.7	5th
Bridge #11	89.5	7th	89.5	4th	89.5	7th	89.5	8th
Bridge #8	88	8th	88	5th	88	8th	88	9th
Bridge #12	88	9th	88	6th	88	9th	88	9th
Bridge #13	75	10th	75	8th	75	10th	75	13th
Bridge #10	71.9	11th	71.9	9th	71.9	11th	71.9	14th
Bridge #2	61.7	**12th**	61.7	11th	61.7	12th	86.1	**11th**
Bridge #14	46.6	**13th**	46.6	13th	46.6	13th	83.1	**12th**
Bridge #1	17	**14th**	17	14th	17	14th	91.7	**5th**

4.4.3 Breakdown of Bridge Resilience by Resilience Indicators

Fig. 4-5 shows the breakdown of each bridge's Resilience into its 5 bridge resilience indicator components. The figure shows that the abutment washout resilience indicator is dominant for these 14 bridges, followed by deck flooding. If both abutment washout and deck flooding indicator scores are large, the bridge climate change Resilience will be high. Where those 2 indicator scores are low, the bridge Resilience is low. Because a single span bridge collapses completely when one or both abutments are washed out by extreme flooding, the proposed method captures effectively the critical importance of abutment washout in the survival of a highway bridge in the presence of extreme flooding.

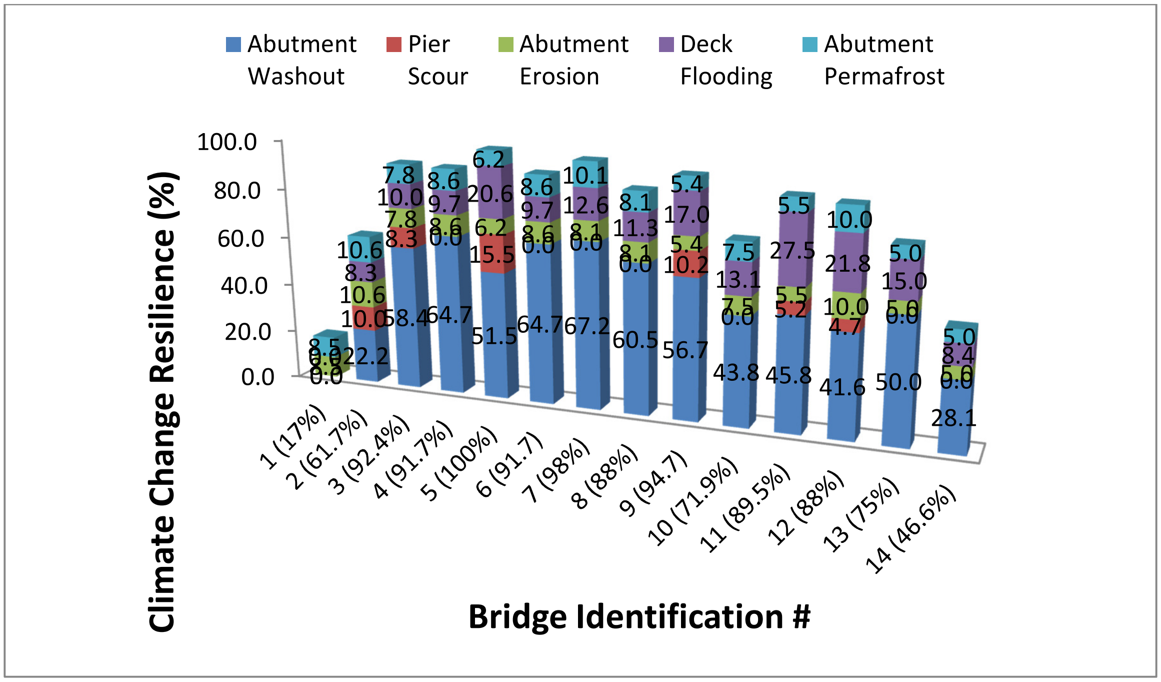


Fig. 4-5 Components of a Bridge's Climate Change Resilience Rating

In contrast, pier scour is more likely to afford advance warning and so it likely attracts much lower resilience indicator weight than abutment washout, which leads to lower bridge Resilience contribution from pier scour as a *resilience indicator*. For these 14 bridges, the abutments, being mostly supported on steel piles, are very resilient, which suggests that deep foundations should be the first choice for highway bridges in cold regions.

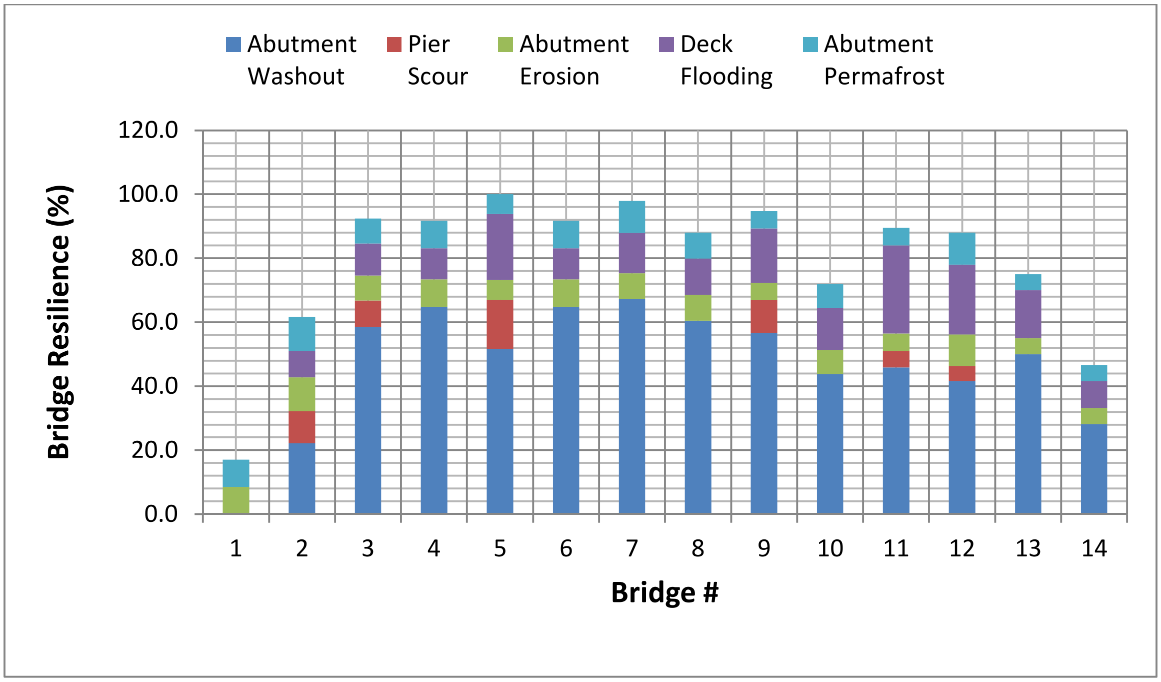


Fig. 4-6 Resilience Indicators as Predictors of Highway Bridge Resilience

Fig. 4-6 shows that for these 14 bridges, abutment washout is by far the most reliable predictor of the overall climate change resilience of the bridges: the bridge resilience is low if the abutment washout resilience indicator score is low, and bridge resilience is high if the abutment washout resilience indicator score is high. Pier scour, on the other hand, is not nearly as determinative: Fig. 4-6 shows that low pier scour resilience scores correspond to high bridge resilience just as high pier scour resilience scores correspond to high bridge resilience. That is because even if 100% of bridge resilience is contributed by one resilience indicator while zero percent is contributed by each of the other 4 resilience indicators, the bridge resilience is always calculated as the sum of the 5 resilience indicators such that there will be data points in which 100% bridge resilience will pair up with one or more zero percent resilience indicator(s). It should be noted that Bridge #5 achieved 100% Resilience because it rated at maximum on all the capacity measures. A bridge will always score 100% on Resilience if it rates at a maximum on all capacity measures, irrespective of the weights distribution among the resilience indicators.

Fig. 4-6 also shows that abutment washout and deck flooding are the 2 most important determinants of the bridge resilience, and they are both associated with the bridge's hydraulic capacity. This leads to the conclusion that, in cold regions, the size of the channel opening under the bridge will be a very important factor determining the climate change resilience/vulnerability rating of highway bridges as this century ages.

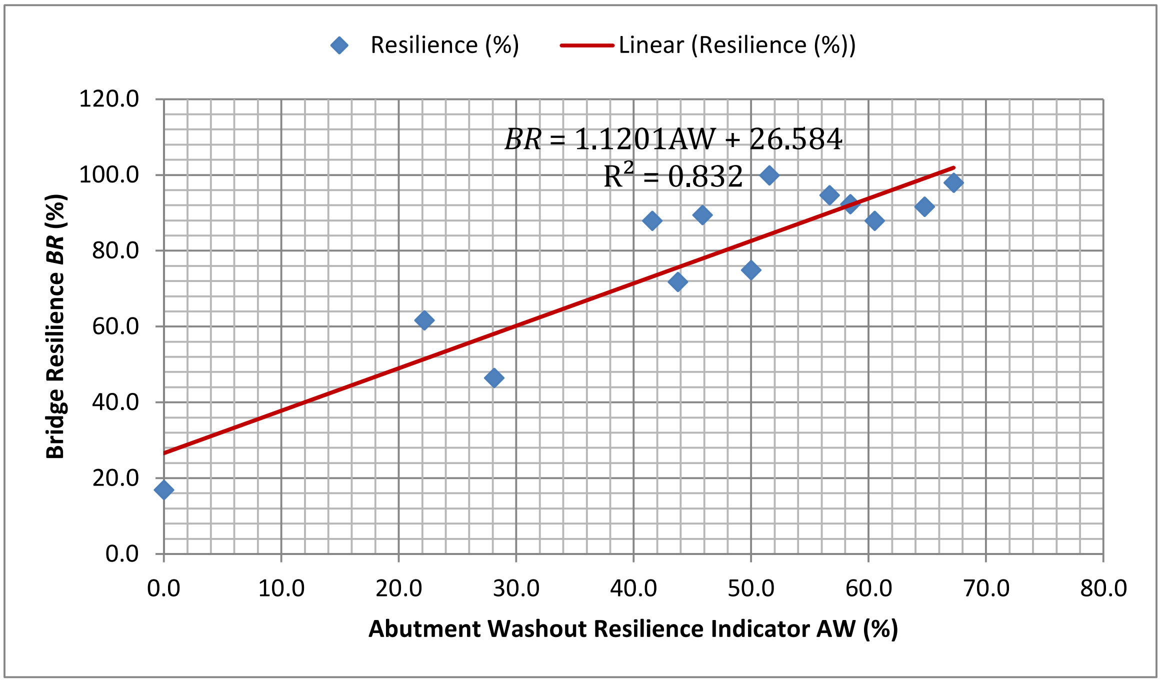


Fig. 4-7 Relationship: Abutment Washout Resilience Indicator Vs Bridge Resilience

Fig. 4-7 shows the plot of abutment washout versus Bridge Resilience (*BR*) for the 14 bridges used for the demonstration of the performance of the proposed method. The graph of Fig. 4-7 shows that, as stated earlier, the bridge's resilience improves with higher abutment washout resilience. Given that the bridge's resilience also depends on 4 other resilience indicators, the coefficient of determination of 0.83 is considered very high.

Based on Fig. 4-7, Bridge Resilience for these 14 bridges is related to Abutment Washout by Equation (4-2).

$$\text{Bridge Resilience } BR = 1.1201AW + 26.584 \qquad (4\text{-}2)$$

The conclusion, therefore, is that in cold regions, for vulnerability of highway bridges to climate-triggered extreme events, if the bridge abutments are robust and resilient, the bridges are half-way there in attaining resilience and immunity from collapse.

4.5. Summary

- A method has been devised for extending the asset management scope for highway bridges beyond the usual bridge condition monitoring to incorporate climate change resilience rating of highway bridges.
- The method provides for a procedure for determining *weights* to be applied to each resilience indicator based on replacement cost, failure consequence, and user cost/inconvenience.
- The method also provides for the *Rating* of the bridges against climate-related capacity measures.
- The method comes with a *Rating Guide* that transportation agencies can use for climate change resilience rating of highway bridges.
- By applying the said procedure to fourteen (14) highway bridges in the Canadian Arctic, it has been illustrated how significant public investments in infrastructure improvement could be laid waste by the failure of public transportation agencies to consider climate-related bridge resilience indicators in the design, rehabilitation, and asset management practices for highway bridges.
- Abutment Washout is the main factor controlling the resilience rating of bridges.
- For highway bridges in cold regions, robust and resilient abutments significantly increase the probability that the bridge will not collapse or experience loss of service when it encounters a climate-triggered extreme event.
- Unless abutment washout, abutment erosion, and melting-permafrost instability are all ruled out, pile foundation should be the first option for abutment and pier footings supporting highway bridges over water crossings in cold regions such as the Canadian Arctic.

Chapter 5

Magnitude of Climate-Triggered Extreme Load that Produces Bridge Failure

5.1. Introduction

The Canadian Highway Bridge Design Code (Canadian Standards Association 2014) defines load factors and load combinations for use with specified load types, for the various limit states at which the bridge's load capacity is to be calculated. One of the limit states, namely, the ultimate limit state (ULS), is defined to represent the magnitude of loading that would fully exhaust the factored resistance of the structure, resulting in failure of a component or collapse of the entire bridge structure. For example, a factor of 1.7 is stipulated for truck live loads under ultimate limit state ULS-1 to provide a safety margin of 70% on the nominal live load effects, which margin covers uncertainties in estimating the applied loads, overloads, etc.

The Code also specifies ultimate limit state ULS-7 comprising 0.8W and 1.3A (where W is Wind Load and A is Ice Accretion Load). However, the design of most highway bridges is governed by ULS-1, which comprises 1.7*L and α_D*D (where L is Live Load, D is Dead Load, 1.7 is load factor for Live Load, and α_D is load factor for Dead Load).

As was pointed out in Chapter 3, one approach to accounting for climate-triggered extreme loads in highway bridge design or load evaluation would be to estimate or forecast the magnitude of *Ice Accretion* and *Wind* loading, say, for a bridge site, then check if the bridge has adequate strength to withstand the estimated load. However, the bridge might be capable of sustaining higher levels of these extreme loads based on the design for other load combinations. The question, then, is how much higher magnitudes of these extreme loads can the bridge withstand before failure?

To answer that question and to complement the resilience rating against climate-triggered extreme *events* that was presented in Chapter 4, a method for highway bridge resilience rating against climate-triggered extreme *loads* is developed in this chapter. As discussed earlier, the governing load combination at the ULS limit state is usually a combination of factored live and dead loads. Accordingly, what is proposed here is a new load case, say, ULS-10, which is derived from the *usual* governing limit state (ULS-1). The proposed method aims to define the reserve strength available (which is 0.7L) to sustain extreme climate loading (e.g. ice accretion extreme load) at a bridge site in the presence of un-factored live load and un-factored dead load as depicted in Equation (5-1).

$$\begin{cases} \text{ULS-1} = 1.7L + \alpha_D D \\ \text{ULS-10} = 1.0L + A + \alpha_D D \end{cases} \tag{5-1}$$

Where:

L, D, and A are live, dead, and ice accretion load, respectively, A = 0.7L, and $\alpha_D = 1.0$ in Eqn. (5-1).

The philosophy behind the above definition of the new load case is that *some* ice accretion can be present on a structure such as a steel Through-Truss bridge and normal traffic would still cross the bridge. Under that condition, the bridge would still be expected to fully sustain factored dead plus factored live loads at the ultimate limit state. But when the thickness of ice on a truss member is considerable (e.g., 1,000 mm), it is unlikely that a truck exceeding the legal weight limit would be permitted on that bridge. In that scenario, it would be of interest to know what magnitude of ice accretion load the bridge could withstand when normal (un-factored) live load is present on the bridge. This can be calculated as the equivalent thickness of ice accretion that corresponds to the 70% live load by which live load is magnified at the ULS-1 limit state. The procedure for doing this was described in Chapter 3 for ice accretion and pier scour extreme loads. While the concept can be applied to various climate-triggered extreme loads, only ice accretion and pier scour are discussed in order to limit the scope of this research.

In this chapter, the new methodology developed in Chapter 3 is applied to the study of the structural-capacity vulnerability rating of highway bridges against climate-triggered extreme loads. A steel through-truss bridge is analysed for the study of ice accretion extreme load case while a concrete girder bridge with single-stem concrete piers is used for the study of the climate-triggered pier scour extreme load case.

5.2. Ice Accretion Extreme Load – Case of a 2-Span through-Truss Bridge (Bridge #12)

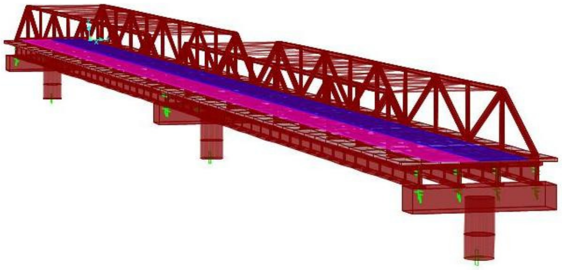
The bridge studied here is modelled after the Lewes River Bridge on the Alaska Highway in Yukon, which comprises 2 spans, each 76.2 metres long (Fig. 5-1, 5-2, and 5-3). The bridge was built in 1955 and was given a major upgrade in 2007 (including a full concrete deck replacement, earthquake-resisting friction-pendulum bearings, and truss strengthening). The following results were obtained using the *CSiBridge* structural analysis software (Computers & Structures Inc. 2014). The results were then used for ice accretion failure load analysis using the new method.

$q_1 = 1$ kN/m	uniformly distributed unit ice accretion load on all exposed truss members
$F_1 = 26.5$ kN	axial force in Member M_{ms} caused by $q_1 = 1$ kN/m
$\gamma_{ice} = 9.8$ kN/m^3	unit weight of ice
$F_{ms} = 95.4$ kN	un-factored truck live load axial force in Member M_{ms}
$F_{ice} = 66.8$ kN	available ice accretion axial force capacity (70% of F_{ms})
$b = 0.30$ m	width of *Bottom Chord* member
q_{ice}	uniformly distributed ice accretion load corr. to F_{ice} (kN/m)
t_{ice}	thickness of accreted ice (m)
$A = 0.30$ m^2	area of accreted ice on 1 metre length of truss member

$$t_{ice} = [F_{ice} / F_1] / [A * \gamma_{ice}] = [66.8 \text{ kN} / 26.5 \text{ kN}] / [0.30 \text{ m}^2 * 9.8 \text{ kN/m}^3] = 0.85 \text{ metre} \tag{5-2}$$

The thickness of ice is 0.85 metre.

From the above analysis, it is observed that since it would take almost 1 metre thickness of ice on the truss members to cause failure, failure is unlikely under ice accretion loading and the bridge can be considered to have adequate strength reserve against ice accretion extreme loading. By convention introduced in Chapter 6, the example bridge would be rated at 0% vulnerable (Resilience: 100%, Vulnerability: 0%) on climate-triggered ice accretion extreme load.



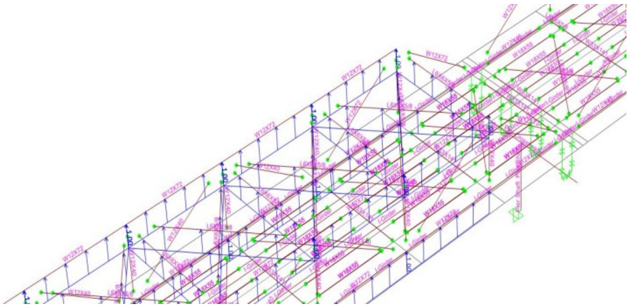


Fig. 5-1
Two-Span Through Truss Bridge subjected to Ice Accretion Loading (*CSiBridge* structural analysis software)

Fig. 5-2
Applied Ice Accretion Loading: 1kN/m on all Steel Surfaces exposed to Ice (*CSiBridge* structural analysis software)

5.3. Pier Scour Extreme Load - Case of Concrete Pier in an 8-Span Bridge

The major parameters involved in the calculation of the scour load capacity for a bridge pier were presented in Fig. 3-5 (Chapter 3). These parameters were named as the top of pier elevation (h_{pier}), the 100-year flood elevation (h_{100}), river bed elevation (h_g), and the top of footing elevation (h_f).

The following is an illustration of the proposed method for calculating the magnitude of pier scour that would cause bending failure of a single-stem reinforced concrete pier similar to the piers of the Donjek River Bridge (Bridge #5) on the Alaska Highway in Yukon (Figures 5-4, 5-5, and 5-6). In the example (Fig. 5-4) studied for this research, the pier supports a 78 metres span in an 8-span bridge of total length 300 metres. The bending moment caused by braking force is calculated below in accordance with the provisions of the Canadian Highway Bridge Design Code CAN/CSA-S6 (Canadian Standards Association 2014). The hydrostatic force q (kN/m) exerted on the upstream face of the pier (Fig. 5-4) varies from zero at flood water elevation to its maximum intensity at the riverbed elevation or the top of the pile footing. It should be noted that, for simplicity, hydrostatic forces on the downstream face of the pier are neglected.

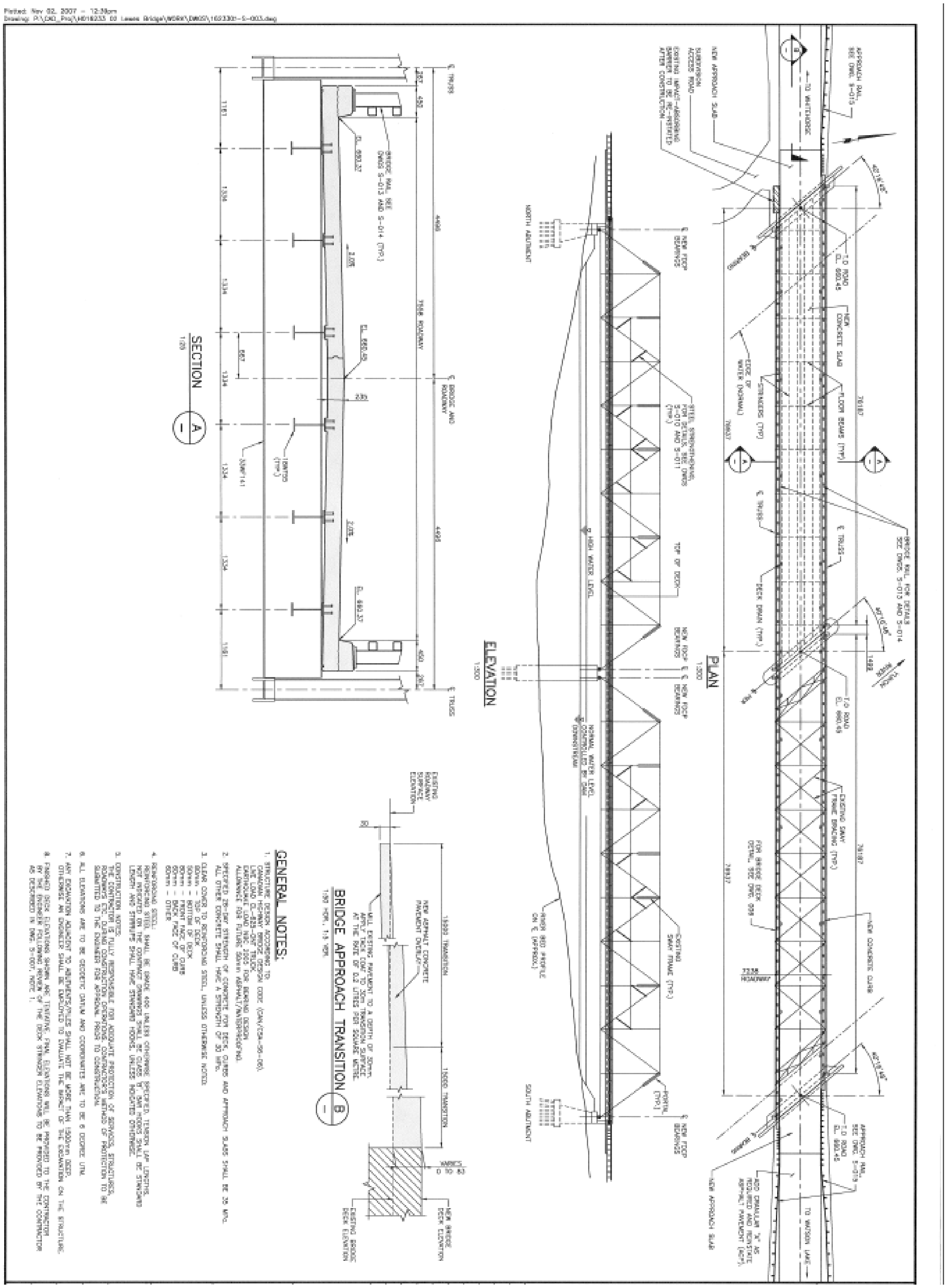


Fig. 5-3 Lewes River Bridge – 2-Span Through-Truss Bridge Similar to the Bridge shown in Figures 5-1 and 5-2

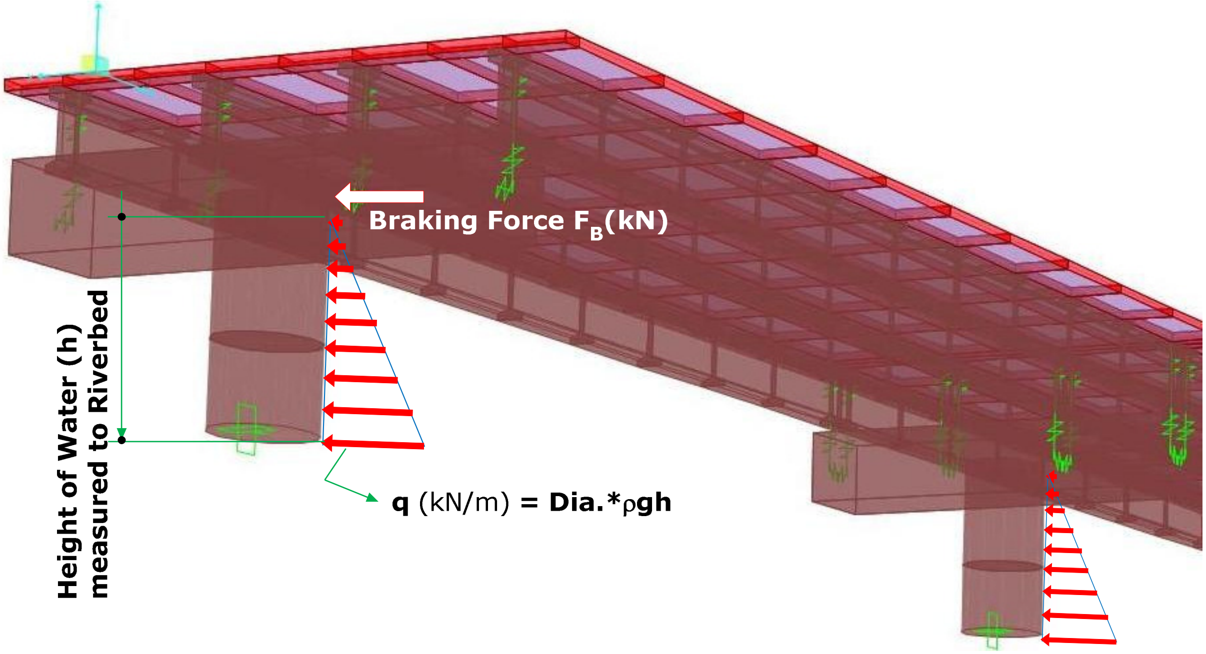


Fig. 5-4 Braking Force plus Pier Scour/Hydrostatic Loading on a 78 metres Bridge Span

The longitudinal Braking Force imposed by a truck is given by (Canadian Standards Association 2014): 180 kN + 10% of 9 kN/m uniformly distributed loading over a 3 metres wide and 78 metres long lane. Each of 2 piers at the ends of the span supports a braking force calculated as follows.

$F_{BRAKING}$ = ½ * [180 kN + 0.1 * 9 kN/m * 78 m] = ½ * [180 kN + 70.2 kN] = 125 kN

Equivalent F_{scour} = 88 kN (70% of un-factored braking force)

Equivalent $M_{scour} = F_{scour} * [h_{pier} + t_f/2]$ = 88 kN * [4.85m + 0.5m] = 470 kNm (5-3)

Pier top elevation z_{top} = – 3.438 m

Pier bottom elevation z_{bot} = – 8.2884 m

Height of pier (h_{pier}) to top of pier footing = 4.85 m [8.2884 m – 3.438 m], Diameter of Pier shaft D = 3.45 m, Thickness of Pier Footing t_f = 1.0 m

Depth from riverbed elev. to top of footing = *d*

Hydrostatic Pressure at height h below water level = 9.81*h* (kN/m^2)

Hydrostatic Force (at height h) q (kN/m) = D*9.81*h = 9.81*D*h

Hydrostatic Moment at Pier/Footing Joint M_q = ½ * h * q * [Lever Arm = h/3 + t_f/2]

$M_q = h^2/2 * 9.81 * D * (h/3 + t_f/2) = 9.81*D*h^3/6 + 9.81*D* t_f*h^2/4$

Hydrostatic Moment $M_q = 9.81*D*h^3/6 + 9.81*D*t_f*h^2/4$ (5-4)

Equating Eqns. (5-3) and (5-4) yields: $h = 3.925$ m

However, this bridge is projected to have 1.15 metres freeboard to the top of pier in the last quarter of this century (calculated based on the 100-year flood discharge and climate-triggered projections for its location). This means that the available height from flood water level to top of footing is 4.85 m – 1.15 m = 3.70 metres. Therefore, the required flood discharge height of water (h = 3.925 m) exceeds the available height from 100-year flood discharge elevation to top of pier footing.

From the above analysis, it is observed that this bridge can withstand the maximum pier scour to which the bridge could be subjected because the amount of scour required to produce bending failure of the pier would call for a greater pier stem height than is available. Nevertheless, because these two heights are close to each other, and that means a small margin of safety, the recommendation would be that engineered apron be installed to protect the piers and to provide a comfortable margin of safety against pier scour loading.

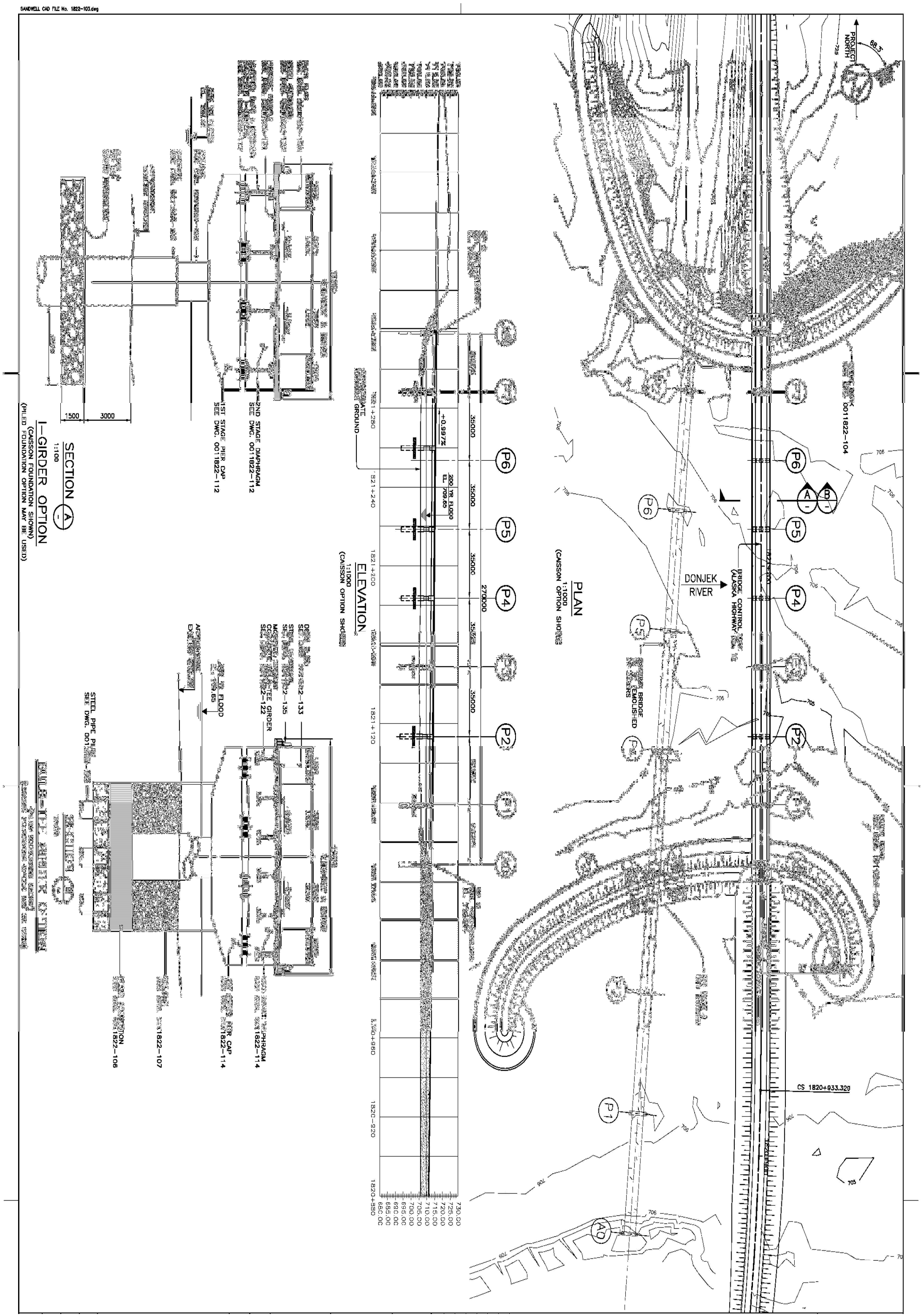


Fig. 5-5 Donjek River Bridge – Single-Stem Piers similar to the Bridge of Figure 5-4

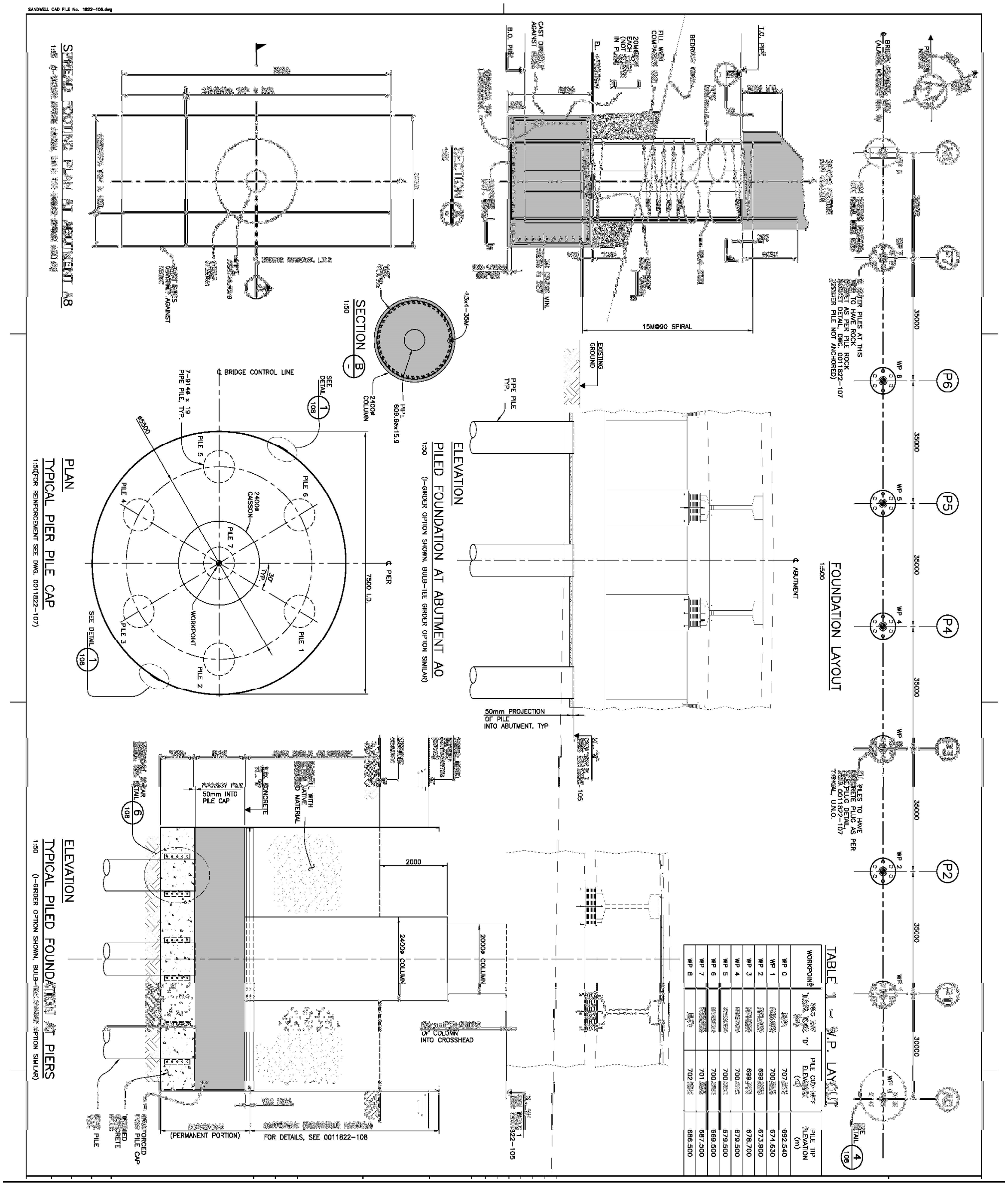


Fig. 5-6 Donjek R. Bridge featuring 2 m Dia Concrete Pier Similar to the Bridge of Fig.5-4

Table 5-1 shows the calculation of pier-scour structural resilience for 6 of the 14 bridges. Those are the 6 bridges with piers, the other 8 being single span bridges. Table 5-2, on the other hand, shows the calculated vulnerability scores for all 14 bridges, for both ice accretion and pier scour extreme load cases.

Table 5-1 Pier Scour Structural Capacity Resilience ($d = 0$ governs over $d \neq 0$)

Bridge #2

Span Length L (m)	19	Pier Top Elev (m)	3.6	Pier Bot Elev (m)	0
Pier Width	6.3	h_{100} (m)	3.1	Top of Ftg Elev h_f	0
Pier Ftg Thickness(m)	1	R-Bed Elev to Ftg Top	*d*		
Available Height of Pier	3.60			Height of Pier to Q_{100} Elev (h_{100})	3.1
$F_{BRAKING}$ (kN)=	98.55	F_{SCOUR} (kN) =	68.985	M_{SCOUR} (kNm)	282.8
Hydrostatic Moment $M_q = 9.81*D*h^3/6 + 9.81*D*t_f*h^2/4$					
Equating M_{scour} to M_q yields: $h = 2.6$ m					
Compare h_{100} to h (where h is height of water reqd. for failure): $h < h_{100}$. Bridge may be at risk. Warrants further study of as-built structural strength and evaluation of need for engineered apron.					

Bridge #3

Span Length L (m)	50	Pier Top Elev (m)	855.8	Pier Bot Elev (m)	850.5
Pier Width	7.1	h_{100} (m)	854.3	Top of Ftg Elev h_f	850.5
Pier Ftg Thickness(m)	1.6	R-Bed to Ftg top (d)	*0*		
Available Height of Pier	5.30			Height of Pier to Q_{100} Elev (h_{100})	3.8
$F_{BRAKING}$ (kN)=	112.5	F_{SCOUR} (kN) =	78.75	M_{SCOUR} (kNm)	480.4
Hydrostatic Force $F_q = 1/2*h*9.81*D*h$					
Hydrostatic Moment $M_q = 1/2*h*9.81*D*h * (h/3 + t_f/2 + d)$					
Equating M_q and M_{SCOUR} yields h = 2.8m					
Compare h_{100} to h (where h is height of water reqd. for failure):				$h < h_{100}$ ⇨ Bridge may be at risk, engineered apron reqd.	

Bridge #5					
Span Length L (m)	78	Pier Top Elev (m)	-3.438	Pier Bot Elev (m)	-8.2884
Dia of Pier Shaft D (m)	3.45	Q_{100} Elev (m)	-4.58	Top of Ftg Elev h_f	-8.2884
Pier Ftg Thickness(m)	1	R-Bed Elev to Ftg Top	*d*		
Available Height of Pier	4.85			Height of Pier to Q_{100} Elev (h_{100})	3.7
$F_{BRAKING}$ (kN)=	125.1	F_{SCOUR} (kN) =	87.57	M_{SCOUR} (kNm)	468.5
Hydrostatic Moment $M_q = 9.81*D*h^3/6 + 9.81*D*t_f*h^2/4$					
By iteration h = 3.9 m Compare h_{100} to h (where h is height of water reqd. for failure): $h > h_{100}$ ⇨ Bridge is safe					

Bridge #9

Span Length L (m)	36.7	Pier Top Elev (m)	8.17	Pier Bot Elev (m)	0
Dia of Pier Shaft D (m)	5.85	Q_{100} Elev (m)	5.72	Top of Ftg Elev h_f	0
Pier Ftg Thickness(m)	1.225	R-Bed Elev to Ftg Top	*0*		
Available Height of Pier	8.17			Height of Pier to Q_{100} Elev (h_{100})	5.7
$F_{BRAKING}$ (kN)=	106.515	F_{SCOUR} (kN) =	74.5605	M_{SCOUR} (kNm)	654.8
Hydrostatic Moment $M_q = 9.81*D*h^3/6 + 9.81*D*t_f*h^2/4$					
Equating M_{scour} to M_q yields: h = 3.56 m					
Compare h_{100} to h (where h is height of water reqd. for failure): $h < h_{100}$. Bridge may be at risk. Warrants further study of as-built structural strength and evaluation of need for engineered apron.					

Bridge #11

Span Length L (m)	67.6	Pier Top Elev. (m)	17.4	Pier Bot Elev (m)	0
Dia of Pier Shaft D (m)	4.7	Q_{100} Elev. (m)	10.4	Top of Ftg Elev h_f	0
Pier Ftg Thickness(m)	1.8	R-Bed Elev. to Ftg. Top	*0*		
Available Height of Pier	17.40			Height of Pier to Q_{100} Elev (h_{100})	10.4
$F_{BRAKING}$ (kN)=	120.42	F_{SCOUR} (kN) =	84.294	M_{SCOUR} (kNm)	1542.6
Hydrostatic Moment $M_q = 9.81*D*h^3/6 + 9.81*D*t_f*h^2/4$					
Equating M_{scour} to M_q yields: h = 5.1 m					
Compare h_{100} to h (where h is height of water reqd. for failure): $h < h_{100}$. Bridge may be at risk. Warrants further study of as-built structural strength and evaluation of need for engineered apron.					

Bridge #12

Span Length L (m)	76.9	Pier Top Elev. (m)	14.6	Pier Bot Elev (m)	0
Dia of Pier Shaft D (m)	6.7	Q_{100} Elev. (m)	12.6	Top of Ftg Elev h_f	0
Pier Ftg Thickness(m)	3.1	R-Bed Elev. to Ftg Top	*0*		
Available Height of Pier	14.60			Height of Pier to Q_{100} Elev (h_{100})	12.6
$F_{BRAKING}$ (kN)=	124.605	F_{SCOUR} (kN) =	87.2235	M_{SCOUR} (kNm)	1408.7
Hydrostatic Moment $M_q = 9.81*D*h^3/6 + 9.81*D*t_f*h^2/4$					
Equating M_{scour} to M_q yields: $h = 3.9$ m					
Compare h_{100} to h (where h is height of water reqd. for failure): $h < h_{100}$. Bridge may be at risk. Warrants further study of as-built structural strength and evaluation of need for engineered apron.					

Table 5-2 Structural Capacity Vulnerability – 14 Bridges

Bridge	Year Built	Year Upgraded	Spans, Span Length (m)	Number of Lanes	Pier Scour (0%) Fail (100%)	Ice Accretion Pass (0%) Fail (100%)
1	2	3	4	5	6	7
Bridge #1	1968	2010	1 (36)	2	N/A	N/A
Bridge #2	1963	2009	4 (75)	2	100	N/A
Bridge #3	2008	-	2 (100)	2	100	N/A
Bridge #4	2009	-	1 (80)	2	N/A	N/A
Bridge #5	2007	-	8 (270)	2	0	N/A
Bridge #6	2006	-	1 (68)	2	N/A	N/A
Bridge #7	1947	2005	1 (61.2)	2	N/A	0
Bridge #8	1947	2005	1 (48.8)	2	N/A	0
Bridge #9	1946	2006	3 (89.4)	2	100	N/A
Bridge #10	1963	2006	1 (21.3)	2	N/A	N/A
Bridge #11	1944	2006	10 (445.9)	2	100	N/A
Bridge #12	1955	2007	2 (152.4)	2	100	0
Bridge #13	1943	2010	1 (18.8)	2	N/A	N/A
Bridge #14	1944	2010	1 (18.6)	2	N/A	N/A

5.4. Summary

A practical approach to determining the magnitude of failure-level climate-triggered extreme load has been developed in the thesis. The method has been applied to all the relevant projects from the inventory of the bridges used in this study. All of the three Through Truss bridges in the inventory are found to be resilient to ice-accretion, while five of the six multi-span bridges were found vulnerable to pier scour effect.

To protect from pier scour, many of these bridges have protective aprons/riprap. What is not known is whether the aprons are designed or engineered for the projected demands. Further, the concrete piers for these bridges may well have more than enough reinforcement to withstand the bending induced by the hydrostatic forces.

The through-trusses of Bridges #7 and #8 have the same configuration as that in Bridge #12, and have been awarded a pass (0%) on ice accretion vulnerability.

Chapter 6

Multi-Criteria Ranking of Competing Bridge Projects

6.1. Introduction

The concepts of depreciation, scheduled maintenance, and scheduled budgeting for the replacement of physical assets are receiving greater attention today among transportation agencies in North America and elsewhere around the world. A Bridge Management System (BMS) is an asset management tool of transportation agencies. Transportation agencies that already have a BMS are looking for ways to improve the capability of their systems with respect to the number of alternative projects and the length of the programming horizon that the systems can process. A major impediment to the processing of many alternatives per bridge and undertaking economic analysis over a longer time horizon is the lengthy computer run time that is involved when the inventory is larger than a few thousands.

As earlier indicated, the method comprises a criterion *rating* system and *weights* derived from the said criteria rating for each proposed criterion so that the rating of each bridge project on the various criteria can be combined into a single index. Here the proposed method is demonstrated using the following four criteria: bridge performance, utility, vulnerability to climate-triggered extreme events, and vulnerability to climate-triggered extreme loads. The procedure is depicted in the flowchart of Figure 6-1 (repeated from Fig. 3-6).

The following formulae were proposed in Equations (3-8) to (3-11) for the rating of each bridge on the criteria described above.

Bridge Performance: $\zeta = 100\{\alpha_i / \alpha_{max} \mid 1 \le i \le N\}$ (6-1)

Agency Benefits: $\chi = 100\{\eta_i / \eta_{max} \mid 1 \le i \le N\}$ (6-2)

Extreme Events Vulnerability: $\tau = 100 - Resilience\,\%$ (6-3)

Extreme Loads Vulnerability: $\Omega = \{\Omega_i = 0 \text{ (Pass) or } 100 \text{ (Fail)} \mid 1 \le i \le N\}$ (6-4)

$Opt\text{-}I(x_i) = \Sigma\{W_{\zeta i} * \zeta_i, W_{\chi i} * \chi_i, W_{\Omega i} * \Omega_i, W_{\tau i} * \tau_i(x) \mid 1 \le i \le N\}$ (6-5)

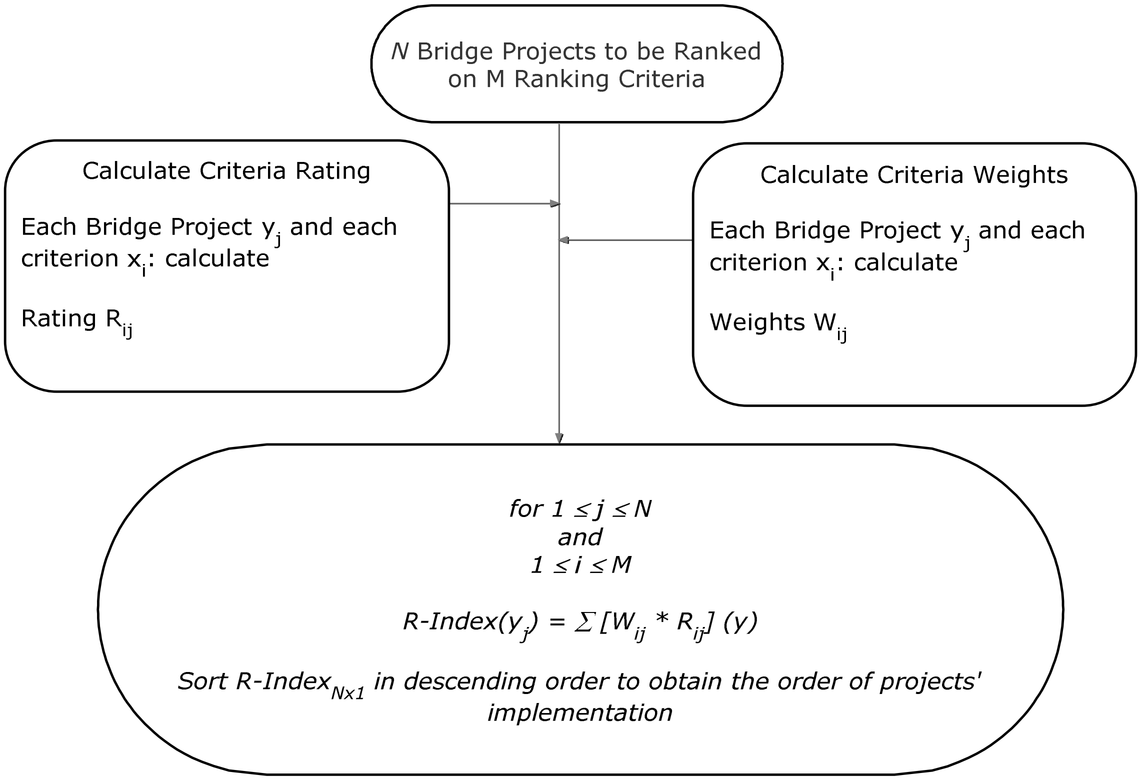


Fig. 6-1 Flow Chart – Direct, Non-Iterative, Multi-Criteria Ranking of Competing Bridge Projects

In the above equations, N is the number of projects to be programmed for implementation, $\boldsymbol{\alpha}_i$ is the Equalized BCI Enhancement per \$100,000 cost of Project x_i, $\boldsymbol{\alpha}_{max}$ is the maximum Equalized BCI Enhancement per \$100,000 cost of N Projects, $\boldsymbol{\eta}_i$ is the Equalized Agency Benefit per dollar cost of Project x_i, $\boldsymbol{\eta}_{max}$ is the maximum Equalized Agency Benefit per dollar cost of N Projects, Resilience % is the Bridge Resilience (BR) as proposed in Chapter 4, and W_{ji} is the weight for Project y_j on Criterion x_i, $i = \zeta, \chi, \tau$

Further, a mathematical formula for calculating the weight to be assigned to each criterion was formulated in Chapter 3 such that greater weight is assigned to those criteria on which the bridge ranks high relative to other bridges while lower weight is assigned to those criteria on which the bridge ranks low relative to the other bridges listed for intervention. That way a bridge that is most vulnerable against climate-triggered extreme events – but with little to recommend it on bridge performance and utility criteria – would still be ranked at the top or very near the top of the ranking table, just as a bridge that is very strong on the latter 2 criteria while very resilient (very low Vulnerability) against extreme climate events would undoubtedly also float to the top or very near the top of the ranking table.

The alternative is what the one-criterion optimization schemes have done, namely, assign a weight of 1.0 to the bridge performance criterion (i.e. optimization is undertaken with respect to only one criterion), for example, so that the bridge with the highest climate-triggered extreme event vulnerability drops to the bottom of the ranking table, and the decision maker has to manually search for it and bring it to the top of the table to eliminate the risk of its collapse. But having to operate that way would defeat the purpose of automation of the Bridge Management System.

The following formula was proposed in Equation 3-6 for criterion weight calculation to permit all criteria to be simultaneously accounted for in the multi-criteria ranking.

$$W(x) = (\gamma\lambda)_i / \sum_{i=1}^{i=n} \gamma_i \lambda_i \,(x) \qquad \text{(6-6)}$$

In the above equation, W is the weight calculated for each ranking criterion x_1 to x_n; γ is the weight parameter related to the ranking of the bridge on the criterion under consideration; and λ = the bridge's score (maximum = 100%) on the criterion under consideration.

6.2. Demonstration/Implementation of the Method

Tables 6-1 (repeated from Table 3-11), 6-2 (repeated from Table 3-12), and 6-3 show 10 projects to be programmed for implementation over a 10-year period. All 10 projects are major rehabilitation intervention, each comprising concrete deck replacement, new bearings, new traffic barriers, and more. The projects are ranked based on 3 criteria, namely, bridge condition improvement per dollar cost of intervention (or performance/cost), agency benefits per dollar cost of intervention (or utility/cost), and vulnerability to climate-triggered extreme events. Each of these criteria is deemed important enough to single-handedly decide the programming of a bridge project ahead of other bridge projects slated for implementation, which would happen where a project ranks very high on one criterion while ranking very low on the other 2 criteria.

Table 6-1
Bridge Condition and Agency Benefits Indices

Bridge 1	New BCI 2	Old BCI 3	Benefits [$] 4	Cost [$]¥ 5	δ_{BCI}/Cost¥¥ 6	Benefits/ Cost 7
Bridge #1	87.50	48.47	3,752,884	5,003,800	0.78	0.75
Bridge #2	90.03	51.46	3,109,803	3,494,000	1.10	0.89
Bridge #3	69.35	51.5	498,000	600,000	2.98	0.83
Bridge #4	71.32	53.5	462,000	600,000	2.97	0.77
Bridge #5	74.95	54.9	2,070,000	1,800,000	1.11	1.15
Bridge #6	90.03	64.9	763600	830,000	3.03	0.92
Bridge #7	69.93	49	8,549,000	8,300,000	0.25	1.03
Bridge #8	74.57	51	1,794,000	2,600,000	0.91	0.69
Bridge #9	88.72	55.13	896,970	1,031,000	3.26	0.87
Bridge #10	86.41	52.76	603,710	827,000	4.07	0.73
Total Cost				25,085,800		

¥ Bridge Rehabilitation Cost

¥¥ BCI Improvement per $100,000 spent on rehabilitation

6.2.1. Ranking of the Projects

Table 6-3 shows that Bridge #5 ranks 1st overall among the 10 projects and does so based on its 1st place ranking on the utility criterion. Recall that the utility criterion represents the savings in intervention cost accruing from undertaking the project now rather than postponing it till the end of the 10-year planning horizon when the bridge would have deteriorated much further and therefore much more expensive to rehabilitate. From that perspective, Bridge #5 would be the worst choice for delay.

Bridge #7 comes in second, based on its strong performance (2nd Place) on the utility criterion. Bridge #10 is 3rd, buoyed by 1st place ranking on bridge performance. Bridge #1 is 4th, driven by its 1st place ranking on climate-triggered extreme events. Most of the remaining 6 projects attain their placement based on an average to above-average showing on 2 of the 3 criteria.

The four projects at the top of the ranking table (Table 6-3), namely, Bridges #5, #7, #10, and #1 show that, under budget constraint, the proposed method does, in one fell swoop, select projects for implementation such that not only those projects that produce the highest overall *inventory performance* per dollar spent are programmed early, but also those projects that serve to negate *vulnerability to sudden bridge failure occasioned by climate-triggered extreme events* as well as projects that attract the highest non-performance *benefits* for tax payers.

Table 6-2

Equalization of Bridge Condition and Agency Benefits Indices

Bridge	Year Built	Year Upgraded	Spans, Span Length (m)	Number of Lanes	BCI/Cost[¥] Ratio A	Converted BCI/Cost $100*A/A_{max}$ %	Benefit/Cost Ratio B	Converted Benefit/Cost $100*B/B_{max}$ %
1	2	3	4	5	6	7	8	9
Bridge #1	1968	2010	7 (290)	2	0.78	19.3	0.75	65.0
Bridge #2	1963	2009	4 (75)	2	1.10	27.1	0.89	77.4
Bridge #3	1947	2005	1 (61.2)	2	2.98	73.1	0.83	72.2
Bridge #4	1947	2005	1 (60.0)	2	2.97	73.0	0.77	67.0
Bridge #5	1946	2006	3 (89.4)	2	1.11	27.4	1.15	100.0
Bridge #6	1963	2006	1 (21.3)	2	3.03	74.4	0.92	80.0
Bridge #7	1944	2006	10 (445.9)	2	0.25	6.2	1.03	89.6
Bridge #8	1955	2008	2 (152.4)	2	0.91	22.3	0.69	60.0
Bridge #9	1943	2010	1 (18.8)	2	3.26	80.0	0.87	75.7
Bridge #10	1944	2010	1 (18.6)	2	4.07	100.0	0.73	63.5

[¥] Bridge Rehabilitation Cost

Table 6-3

Ranking – Bridge Condition, Agency Benefits, and Extreme Events

Bridge #	¥¥BCI Index %	Ranking	Percentile	Weight	¥Benefit Index %	Ranking	Percentile	Weight	Climate Vulnerability %	Ranking	Percentile	Weight	Σ(Weights)	Ranking Index	Final Ranking
1	2	3	4	*5*	6	7	8	9	10	11	12	13	14	15	16
5	27.4	6	0.40	*0.11*	100.0	1	0.90	0.89	5.3	9	0.10	0.01	1.0	91.7	1st
7	6.2	10	0.00	0.00	89.6	2	0.80	0.97	10.5	8	0.20	0.03	1.0	87.3	2nd
10	100	1	0.90	0.65	63.5	9	0.10	0.05	53.4	2	0.80	0.31	1.0	84.0	3rd
1	19.3	9	0.10	0.02	65.0	8	0.20	0.15	83.0	1	0.90	0.83	1.0	79.0	4th
3	73.1	4	0.60	0.60	72.2	6	0.40	0.40	2.0	10	0.00	0.00	1.0	72.7	5th
9	80.0	2	0.80	0.56	75.7	5	0.50	0.33	25.0	5	0.50	0.11	1.0	72.6	6th
6	74.4	3	0.70	0.42	80.0	3	0.70	0.45	28.1	4	0.60	0.14	1.0	70.7	7th
4	73.0	5	0.50	0.59	67.0	7	0.30	0.33	12.0	6	0.40	0.08	1.0	66.2	8th
2	27.1	7	0.30	0.10	77.4	4	0.60	0.57	38.3	3	0.70	0.33	1.0	59.5	9th
8	22.3	8	0.20	0.48	60.0	10	0.00	0.00	12.0		0.40	0.52	1.0	16.9	10th

¥ Agency Benefits per Unit Cost, where Cost is Bridge Rehabilitation Cost
¥¥ BCI Improvement per $100,000 spent on rehabilitation
<u>Example Calculation of Weight using Equation (6-6)</u> → Weight for *BCI Index* for Bridge #5:
Weight = 27.4 * 0.4/(27.4 * 0.4 + 100 * 0.9 + 5.3 * 0.1) = 0.11
<u>Example Calculation of Ranking Index (R-Index) using Equation (6-7)</u> → *R-Index* for Bridge #5:
27.4 * 0.11 + 100*0.89 + 5.3*0.01 = 92.0% ≈ 91.7%

6.2.2. Projects’ Selection under Budget Constraint

Suppose that a Transportation Agency is granted only 50% ($12,542,900) of the total budget ($25,085,800) required to intervene on 10 bridges over a 5-year planning horizon. Based on the cost data in Table 6-1, this budget allocation would cover the intervention cost for the top 3 bridges (Bridges #5, 7, and 10) at a combined cost of $10,927,000, with $1,615,900 left over. Ranked 4th, Bridge #1 would cost $5,003,800 to rehabilitate, and $1,615,900 is not sufficient money to do it. However, in its place Bridges #3 and #9 would be implemented at a combined cost of $1,631,000. So, with 50% of the required budget, this method identifies for implementation 50% (5 of 10) of the bridges requiring intervention.

Now, it is noteworthy that one of the five bridges selected, namely, Bridge #7 (a 450 metres long bridge built in the 1944) would alone take up two-thirds of the available budget ($8,300,000 of $12,542,900). That amount of money could rehabilitate 6 of the 10 bridges if cost minimization were the sole criterion. But the proposed project for Bridge #7 would also save the transportation agency $8,549,000 of the $22,499,967 (one-third) available savings if all 10 bridges received intervention now rather than get delayed till the end of the current planning horizon.

For comparison, the selection of bridge projects based on performance/cost, which is the chosen optimization objective in ***BrM***, would be as follows. The ranking of the 10 projects on the performance/cost criterion is shown in Column 3 of Table 6-3, which shows from 1st Place to 10th Place: Bridges #10, 9, 6, 3, 4, 5, 2, 8, 1, and #7. Given a budget allocation of $12,542,900, 8 of the 10 projects can be executed leaving out only the two most expensive projects, namely, Bridges #7 and #1. But, given that Bridge #1 would be destroyed if the deck is not raised (to avoid deck flooding) and if the shallow abutment foundations are not replaced with steel pile abutments (to avoid abutment washout), delaying intervention for Bridge #1 would result in a catastrophic failure that the transportation agency can't afford. Worse still, ranking on the basis of a lone criterion would mean that Bridge #1 might not even come within view of the decision maker especially if only 8 projects can be implemented out of 100 and Bridge #1 falls in the bottom half of the ranking table for *bridge performance*.

Suppose now that three-quarters (75% or $18,815,000) of the required budget is available for preservation intervention for the 10 bridges. For this budget allocation and as per the ranking in Column 16 of Table 6-3 (all 3 criteria considered), the top 8 bridges would receive intervention, leaving out Bridges 2 and 8. By comparison, ranking solely with respect to the objective of maximum performance at minimum cost, 9 bridge projects would receive intervention, leaving out only Bridge #7, which, at $8,300,000, is the most expensive project and therefore places last (10th) on the BCI/Cost criterion. So, 8 of 10 projects for multi-criteria ranking and 9 of 10 projects for single-criterion ranking would be implemented. The number of projects in both cases is almost even, but, more importantly, the order in which the projects are implemented varies widely for the two cases.

6.2.3. Minimizing Life-Cycle Cost while Maximizing Performance

For multi-objective ranking aimed at a tripod-objective of minimizing the total life-cycle cost of the bridge inventory, maximizing performance, while ensuring that there will be no bridge failures caused by climate-triggered extreme events, the ranking of the 10 bridge projects would remain exactly as shown in Column 16 of Table 6-3 and as earlier discussed.

Based on the data in Table 6-1 (Column 3), the average Bridge Condition Index (BCI) of the 10 bridges before intervention would be 53.3%, and it improves to 80.3% if all of $25,085,000 is spent on the rehabilitation of all 10 bridges. Knowing that there is insufficient budget to attain 80.3% and if the average BCI of the rest of the bridge inventory is at a certain level, say, 65%, it is important to find out what budget could move the average BCI for these 10 bridges to that level and what projects should be undertaken in order to achieve that goal. The algorithm for implementing the proposed method would proceed as follows. First, the algorithm would deduct the old BCI (54.9%) of the highest-ranked project (Bridge #5, Table 6-1, Col 3) from the total BCI of the 10 projects and add the new BCI (74.95%, Table 6-1, Col 2) to the total, calculate the new average for the 10 bridges, and accumulate the project cost for Bridge #5 in order to track the required budget. Continue accumulating projects and costs in the order of the projects ranking of Colum 16 of Table 6-3 until the average BCI of 65% or marginally better is achieved. The selected projects and their total cost are, respectively, the projects that should be implemented and the required budget to attain the inventory-wide average BCI of 65%.

If, on the other hand, the objective is narrowly cast, such as maximizing performance under budget constraint without regard to cost savings or vulnerability to climate-triggered extreme events, the projects ranking would be the one shown in Colum 3 of Table 6-3. To select the projects that would raise the BCI of the entire bridge inventory to 65%, the same algorithm as described in the previous paragraph would apply, but with the projects accumulated in the order of the ranking shown in Colum 3 of Table 6-3. In comparison to the intervention cost to attain the specified system-wide target performance level of 65% with all 3 criteria taken into account, the intervention cost to achieve 65% performance level would be smaller here since this criterion (performance/cost) has minimum cost as its cardinal and only objective.

6.3. Comparison of the Method with BrM (AASHTO, United States)

As described in Chapter 2, the AASHTOWare Bridge Management software or **BrM** (formerly called ***Pontis***), emphasizes project selection to meet a specified *performance target*. To compare the ***BrM*** method with the method proposed in the present research, the 10 projects described above are used. As noted in Chapter 2, the ***BrM*** method chooses the performance criterion as the main ranking criterion, with the utility criterion as the secondary criterion, and no other criteria are considered. Further, where there is sufficient budget to implement all 10 projects, the ***BrM*** method reduces to a one-criterion ranking method with only performance considered and utility completely ignored. But, of course, the order of implementation of the projects is important and the method proposed in this thesis considers all 3 criteria, always, whether or not the budget is limited.

Suppose now that it is desired to improve the average *bridge performance* for these 10 bridges from 53.26% to 80.3%, and suppose that the required budget to achieve this performance target is $25,085,000 (twenty-five million dollars). Further, assume that only half (50%) of the total required budget for the 10 projects, namely, $12,542,900 is available. Following is a description of the optimization analysis and results using the ***BrM*** method, followed by a comparison of the said results with those output by the direct, non-iterative, ranking method proposed here.

For the 10 projects, the ranking based on bridge performance is as shown in Table 6-4 (Columns 2 and 3), which also shows the ranking on the utility criterion (Columns 5 and 6). The list of projects ranked based on the performance criterion, which also satisfies the budget constraint is called List "C" in the ***BrM*** method, and that list is shown in Column 7 of Table 6-4. List "C" (Column 7 of Table 6-4) contains 8 projects in the order of priority, with top priority going to Bridge #10 and the least priority is accorded to Bridge #8. The two projects that do not make the list are Bridge #1 and Bridge #7, and they are excluded because their inclusion would violate the budget constraint criterion. The total cost of these 8 projects is $11,782,000, which is a little below the available budget of $12,542,900. Since the performance target of 80.3% is not met (it takes $25,085,000 to achieve 80.3% performance rating), next, ***BrM*** substitutes the bottom projects in List "C" with the top projects of List "B" (the utility List). The final list and order of projects is shown in Column 8 of Table 6-4, as follows: Bridges #10, #9, #6, #5, and #7. Based on the data for bridge condition index (i.e. bridge performance) before and after intervention (Table 6-1), the improvement in bridge condition index for these 5 bridges are: 33.65%, 33.59%, 25.13%, 20.05%, and 20.93%, which is an average of 13.3% over the 10 projects. The benefits (long-term cost savings) accruing to the transportation agency in implementing the selected 5 projects are $603,710; $896,970; $763,600; $2,070,000; and $8,549,000, which represents an average of $1,288,328.00 over the 10 bridges.

In comparison, the 5 projects selected by the method proposed in this thesis are Bridges #5, #7, #10, #3, and #9 (as presented in *Section 6.2.2* above). Based on the data for bridge performance before and after intervention (Table 6-1), the improvement in bridge condition index for these 5 bridges are: 20.05%, 20.93%, 33.65%, 17.85%, and 33.59%, which is an average of 12.6% over the 10 projects. The benefits (long-term cost savings) accruing to the transportation agency in implementing the selected 5 projects are $2,070,000; $8,549,000; $603,710; $498,000; and $896,970, which represents an average of $1,261,768.00 over the 10 projects.

Table 6-4
“Optimization” using the ***BrM*** Method

Bridge ID 1	BCI/Cost (Max 100%) 2	BCI/Cost Ranking 3	Bridge ID 4	Benefit/Cost (Max 100%) 5	Benefit/Cost Ranking 6	***BrM*** List "C" Performance Only 7	***BrM*** List "C" Performance + Benefit 8
#10	100.0	1	#5	100.0	1	Bridge #10	Bridge #10
#9	80.0	2	#7	89.6	2	Bridge #9	Bridge #9
#6	74.4	3	#6	80.0	3	Bridge #6	Bridge #6
#3	73.1	4	#2	77.4	4	Bridge #3	~~*Bridge #3*~~
#4	73.0	5	#9	75.7	5	Bridge #4	~~*Bridge #4*~~
#5	27.4	6	#3	72.2	6	Bridge #5	Bridge #5
#2	27.1	7	#4	67.0	7	Bridge #2	~~*Bridge #2*~~
#8	22.3	8	#1	65.0	8	Bridge #8	Bridge #7
#1	19.3	9	#10	63.5	9		
#7	6.2	10	#8	60.0	10		
Total Cost						$11.782 m	$12.188 m

The 2 sets of results presented above show very good agreement:

1. the selected projects are almost all the same for both methods (both methods select 5 projects out of 10, and 4 of the 5 projects are identical)
2. the average improvement in bridge performance show 95% agreement (13.3 % improvement using ***BrM*** and 12.6% using the proposed method)
3. the average long-term cost savings accruing from the selected projects show 98% agreement ($1,288,328.00 using ***BrM*** and $1,261,768.00 using the proposed method).

To conclude, the above comparison shows that the new method produces similar results as ***BrM*** while cutting down the computer run time immeasurably compared to ***BrM***. As an extra bonus, the new method performs better than ***BrM*** by the earliest scheduling of intervention for Bridges #5 and #7 compared to ***BrM***, which schedules them last. Bridges #5 and #7 score the highest on the utility criterion, which criterion selects bridges on the basis of what projects would attract the highest project scope and cost if delayed till the end of the current programming horizon.

Further, while the proposed new method is able to detect and prioritize Bridge #1 on account of its climate-triggered extreme event vulnerability, Bridge #1 escapes notice using the ***BrM*** method. This is an important advantage of the new method over ***BrM***.

6.4. Comparison with Weights based on Criteria Ranking (*Prioritization*)

Suppose that the Analytic Hierarchy Process (AHP) was used for ranking the 4 criteria. Further, suppose that the criteria ranking were bridge performance 1st, utility 2nd, climate-triggered extreme event vulnerability 3rd, and climate-triggered extreme load vulnerability 4th. Finally, suppose that based on the above criteria ranking, the weight assignments are 0.50 for 1st-ranked, 0.25 for 2nd-ranked, 0.15 for 3rd-ranked, and 0.10 for 4th-ranked criteria (Table 6-5, Columns 5, 9, 13, and 17). The resulting top 10-ranked of the 30 bridge projects are Bridges #10, #16, #24, #27, #6, #18, #14, #4, #21, and #11 (Table 6-5). Based on the rating of the bridges on the 4 criteria (Table 6-5, Columns 2, 6, 10, and 14), it can be seen that the top-ranked bridges are, for the most part, bridges with high scores on bridge performance and utility, which are the criteria that were subjectively assigned the largest weights. It is important to note that the results show that the above approach fails to pick up Bridge #13 with 98% rating on extreme climate event vulnerability and Bridge #5 with 100% rating on utility. It is equally noteworthy that Table 6-5 shows that Bridge #5 scored 100% on each of utility and climate extreme event vulnerability, and yet it didn’t make it into the top 10 bridges for early implementation.

What the above analysis and discussion show is that *criteria ranking* is *subjective* and it involves *trading off* a criterion in order to have another criterion, which leads to *subjectively prioritizing* projects that score high on that criterion over projects that score low on that criterion, notwithstanding that the latter may have scored very high on other criteria. In other words, the output/outcome of the AHP technique is *prioritization* as distinct from *optimization*. In optimization, we select the best of everything whereas in prioritization we select the best of one thing (i.e. what we select are the projects rating the best on one criterion). Evidently, the AHP technique will not produce *optimization* of bridge projects’ selection. This comparison will be undertaken in greater detail in Chapter 7.

To conclude the present discussion of the differences between the AHP technique (prioritization) and the multi-criteria ranking method proposed in this thesis, the following will be noted.

1. Consider the task of selecting a High School Science Quiz team ("Team A") to compete against other High School Science Quiz Teams in the 2015/2016 academic year. The three science subjects of Mathematics, Physics, and Chemistry will be the quiz topics. The competition will feature a 3-man team from each high school, and the selection pool comprises the top 30 students in the school on the subjects of Mathematics, Physics, and Chemistry. Here is how prioritization and optimization approach the task. Prioritization subjectively decides that Mathematics is the most important science subject and so it selects the three students that placed 1st, 2nd, and 3rd in Math. Optimization, on the other hand, considers that the three science subjects are equally important for the science quiz competition. Therefore, optimization selects, in this order, the student that placed 1st on Physics with 97%, the student that placed 1st in Math with 94%, and the student that placed 1st in Chemistry with 92%.
2. In terms of maximization of the value function, the proposed ranking method does achieve maximization of the value function by assigning the largest weight to the criterion on which the bridge project rates the highest, the second largest weight to the criterion on which the bridge projects rates the next highest, etc.

6.5. Climate Change Vulnerability Vs Risk of Bridge Failure

The *failure risk* associated with climate change vulnerability extends beyond the subject bridge, and the risk level will depend on the availability of detour roads should the bridge be put out of service when it encounters a climate-triggered extreme event. That's because the availability of detour routes is what determines the ability of road users to continue their journey and reach their destinations, thus permitting the mitigation of user inconvenience. The *vulnerability rating* of a bridge, on the other hand, scores the level of deficiency of that specific bridge in withstanding climate-triggered extreme loading, and it does not depend on the serviceability status of other bridges in the roads network.

But, what's better to use for projects' ranking: vulnerability rating or failure risk? It is important to note that, based on the definition of risk R in Equation 6-8, unless the consequence is 1.0 on a scale of 0 to 1, the failure risk will always be numerically smaller than vulnerability rating. Further, *performance* and *utility* pertain only to the bridge in question (without accounting for the serviceability status of the rest of the bridges in the network). Therefore, to ensure "equal treatment" of each ranking criterion, it is logical to continue to base bridge projects' selection on performance, utility, and climate change *vulnerability* (as opposed to performance, utility, and the *risk of failure* triggered by extreme climate events).

Table 6-6 shows climate change vulnerability data for 10 inventory bridges and 20 parametrically-derived bridges, for a total of 30 bridges. The 20 parametric bridges were derived from the 10 inventory bridges by factoring both the climate-triggered extreme event and climate-triggered extreme load rating of the 10 inventory bridges while holding the utility and performance ratings same as the corresponding inventory bridge.

While the calculation of a bridge's climate change *vulnerability* rating has earlier been presented in Chapter 4, the *risk* of roads network disruption is calculated in Table 6-6 as the product of extreme event *Vulnerability* "*V*" times the *Consequence* "*C*" (for road users) of the bridge's failure or loss of service:

$$R = V * C \tag{6–8}$$

In managing a road and bridge network within a jurisdiction, it is important for the transportation agency to ensure that there is no loss or significant deterioration of level of service within travel corridors, but it is even more important for the agency to ensure that there is no collapse of any bridges when subjected to climate-triggered extreme load.

For the 10 bridges of Table 6-6, the calculated *vulnerability* and *risk* scores are plotted in Figures 6-2, 6-3, and 6-4. These three figures show that the Risk curve never floats above the Vulnerability curve. That's because the Consequence C in Equation 6-8 has a maximum value of 1.0 so that the product $V * C$ is never greater than the value of the Vulnerability V. In other words, when the two quantities of Vulnerability V and Risk R are not equal, Vulnerability V is always higher. This indicates that Vulnerability V is the better criterion for use in the multi-criteria ranking of competing bridge projects: the higher a bridge scores on the climate-triggered extreme event vulnerability criterion, the better the chances that the said bridge would be selected for intervention when it competes against other bridges with high scores on the *bridge performance* or *utility* criteria. Notwithstanding the above, it is very important that the transportation agency knows what *risks* the public is exposed to in terms of transportation network disruption should climate-triggered extreme load or extreme event precipitate a bridge failure or loss of service.

6.6. Probability of Bridge Selection for Intervention as a Function of Vulnerability

The *probability of intervention* ρ on a bridge x_i is defined as the difference between 100% probability and the percentage of bridges with a *Ranking Index* greater than the *Ranking Index* of the bridge under consideration. It defines what percentage of the proposed bridge projects are yet to be implemented and indicates that the bridge in question is at the top of the list of those projects that are yet to be implemented:

$$\rho\,(x_i) = 100\% - 100\{\boldsymbol{n}_i/\boldsymbol{N}\} \qquad (6\text{-}9)$$

where:

$\boldsymbol{n}_i$ = the count of bridge projects with ranking index (R-Index) larger than the ranking index of bridge project x_i

$\boldsymbol{N}$ = the total number of projects selected for implementation programming

The concept can be illustrated by considering a set of 10 bridges to be ranked for the order of implementation. A bridge with a 60% probability of intervention is 5th-ranked because 60% probability means that 40% or 4 of the 10 bridges would receive intervention ahead of the bridge in question receiving intervention. In other words, 60% probability indicates that the bridge in question will be next in line for intervention after 40% or 4 of the 10 bridges have received intervention:

$$\text{Probability } \rho\,(5^{th}\text{-Ranked Bridge}) = 100\% - 100\{\boldsymbol{n}_i = 4/\boldsymbol{N}=10\} = 60\%$$

The practical use of this is this: if the bridge projects' budget allocation from the provincial government to the transportation agency is 40%, one can determine at a glance that a bridge with 60% probability will fall just short of making the cut.

Table 6-5 Analytic Hierarchical Process (AHP) *Prioritization* of Bridge Projects' Selection 30 Bridges and 4 Criteria

Bridge #	Performance %	Weight	utility %	Weight	Extreme Events %	Weight	Extreme Loads %	Weight	Σ(Weights)	Prioritization Index	Ranking
1	2	3	4	5	6	7	8	9	10	11	12
10	100.0	0.50	63.5	0.25	87.3	0.15	0	0.10	1	79.0	2
16	84.0	0.50	90.0	0.25	71.9	0.15	0	0.10	1	75.3	9
24	83.0	0.50	83.7	0.25	80.4	0.15	0	0.10	1	74.5	14
27	94.8	0.50	58.3	0.25	71.6	0.15	0	0.10	1	72.7	7
6	74.4	0.50	80.0	0.25	97.5	0.15	0	0.10	1	71.8	6
18	77.7	0.50	80.8	0.25	78.0	0.15	0	0.10	1	70.8	16
14	93.0	0.50	33.0	0.25	88.0	0.15	0	0.10	1	68.0	4
4	73.0	0.50	67.0	0.25	80.4	0.15	0	0.10	1	65.3	20
21	70.0	0.50	63.0	0.25	90.0	0.15	0	0.10	1	64.3	15
11	80.7	0.50	85.0	0.25	17.0	0.15	0	0.10	1	64.2	12
3	73.1	0.50	72.2	0.25	58.4	0.15	0	0.10	1	63.4	22
9	80.0	0.50	75.7	0.25	27.0	0.15	0	0.10	1	63.0	17
17	66.2	0.50	69.6	0.25	68.5	0.15	0	0.10	1	60.8	24
12	72.9	0.50	57.4	0.25	61.7	0.15	0	0.10	1	60.1	25
5	27.4	0.50	100.0	0.25	75.8	0.15	100	0.10	1	60.1	1
15	57.4	0.50	57.0	0.25	94.7	0.15	0	0.10	1	57.2	11
19	60.0	0.50	51.7	0.25	75.0	0.15	0	0.10	1	54.2	26
25	37.5	0.50	92.0	0.25	75.8	0.15	0	0.10	1	53.1	10
22	55.0	0.50	49.7	0.25	79.4	0.15	0	0.10	1	51.8	23
29	68.0	0.50	28.7	0.25	57.0	0.15	0	0.10	1	49.7	27
26	79.0	0.50	14.8	0.25	37.5	0.15	0	0.10	1	48.8	19
13	26.9	0.50	79.8	0.25	98.0	0.15	0	0.10	1	48.1	3
8	22.3	0.50	60.0	0.25	70.4	0.15	100	0.10	1	46.7	5
23	39.0	0.50	71.5	0.25	58.4	0.15	0	0.10	1	46.1	28
2	27.1	0.50	77.4	0.25	79.4	0.15	0	0.10	1	45	18
28	42.3	0.50	80.3	0.25	20.4	0.15	0	0.10	1	44.3	21
1	19.3	0.50	65.0	0.25	90.0	0.15	0	0.10	1	39.4	13
20	40.0	0.50	43.5	0.25	46.6	0.15	0	0.10	1	37.9	29
7	6.2	0.50	89.6	0.25	71.6	0.15	0	0.10	1	36.2	8
30	17.9	0.50	37.4	0.25	27.3	0.15	0	0.10	1	22.4	30

Table 6-6

Individual Bridge's *Vulnerability* Vs *Risk of Disruption* of Roads Network

Bridge #	Extreme Event Vulnerability Rating % (V)	Consequence C	Risk = V * C/100 (Max 1.0)	Bridge #	Extreme Event Vulnerability Rating % (V)	Consequence C	Risk = V * C/100 (Max 1.0)	Bridge #	Extreme Event Vulnerability Rating % (V)	Consequence C	Risk = V * C/100 (Max 1.0)
1	83.0	1.0	0.83	11	17.0	1.0	0.17	21	90.0	1.0	0.90
2	38.3	0.4	0.15	12	61.7	0.4	0.25	22	79.4	0.4	0.32
3	2.0	0.6	0.01	13	98.0	0.6	0.59	23	58.4	0.6	0.35
4	12.0	0.6	0.07	14	88.0	0.6	0.53	24	80.4	0.6	0.48
5	5.3	1.0	0.05	15	94.7	1.0	0.95	25	75.8	1.0	0.76
6	28.1	0.6	0.17	16	71.9	0.6	0.43	26	97.5	0.6	0.59
7	10.5	0.6	0.06	17	89.5	0.6	0.54	27	71.6	0.6	0.43
8	12.0	0.4	0.05	18	88.0	0.4	0.35	28	70.4	0.4	0.28
9	25.0	0.6	0.15	19	75.0	0.6	0.45	29	77.0	0.6	0.46
10	53.4	0.6	0.32	20	46.6	0.6	0.28	30	87.3	0.6	0.52

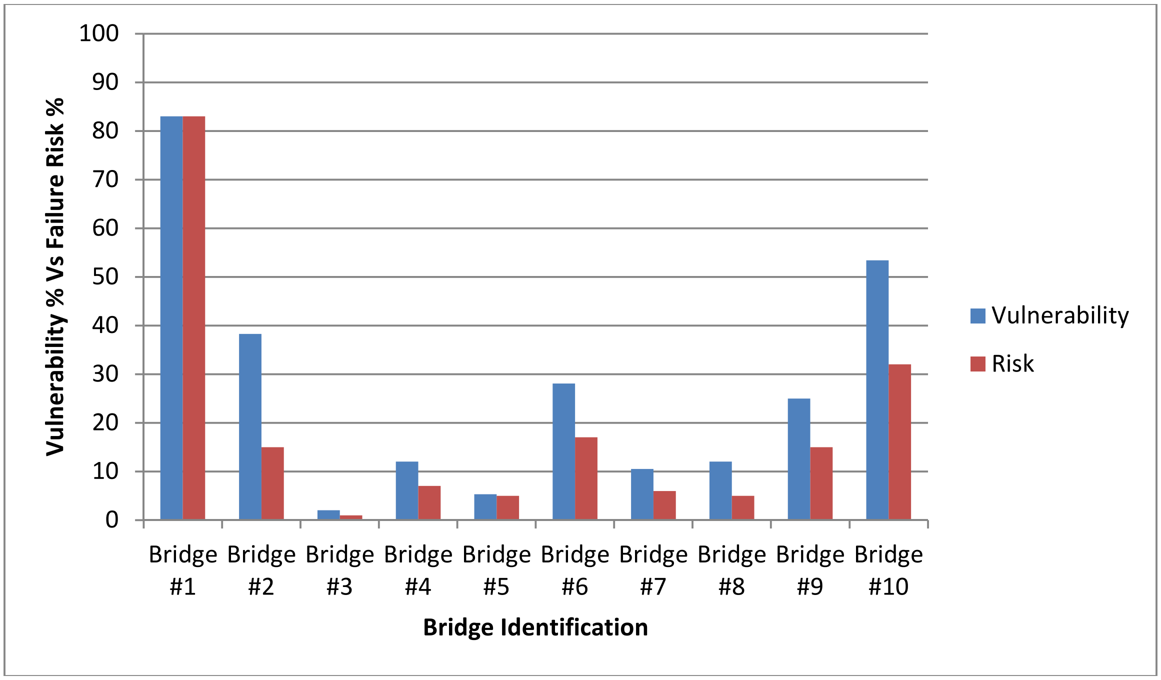


Fig. 6-2 Extreme Event Vulnerability Rating Vs Risk of Roads Network Disruption (Bridges #1 to #10)

Only the top 40% of bridges on the Ranking Index column of the spreadsheet will receive intervention. If, on the other hand, 50% of the required budget allocation is made, then the bridge with 60% probability will receive intervention because it falls within the top 50% of the bridges on the Ranking Index table.

Fig. 6-7 shows a plot of Climate-triggered Extreme Event Vulnerability rating versus both the bridge's multi-criteria Ranking Index score and Probability of Intervention for 10 of the parametrically-derived bridges (Bridges #11 to #20). The calculated ranking indices for the 10 bridges are shown in Table 6-8. A regression analysis of the graph of Fig. 6-6 yields the following relationship for Ranking Index and Probability of Intervention, respectively.

$$R\text{-}Index = 0.27V + 61.388 \qquad (6\text{-}10)$$

$$\rho = 0.57V - 13.68 \qquad (6\text{-}11)$$

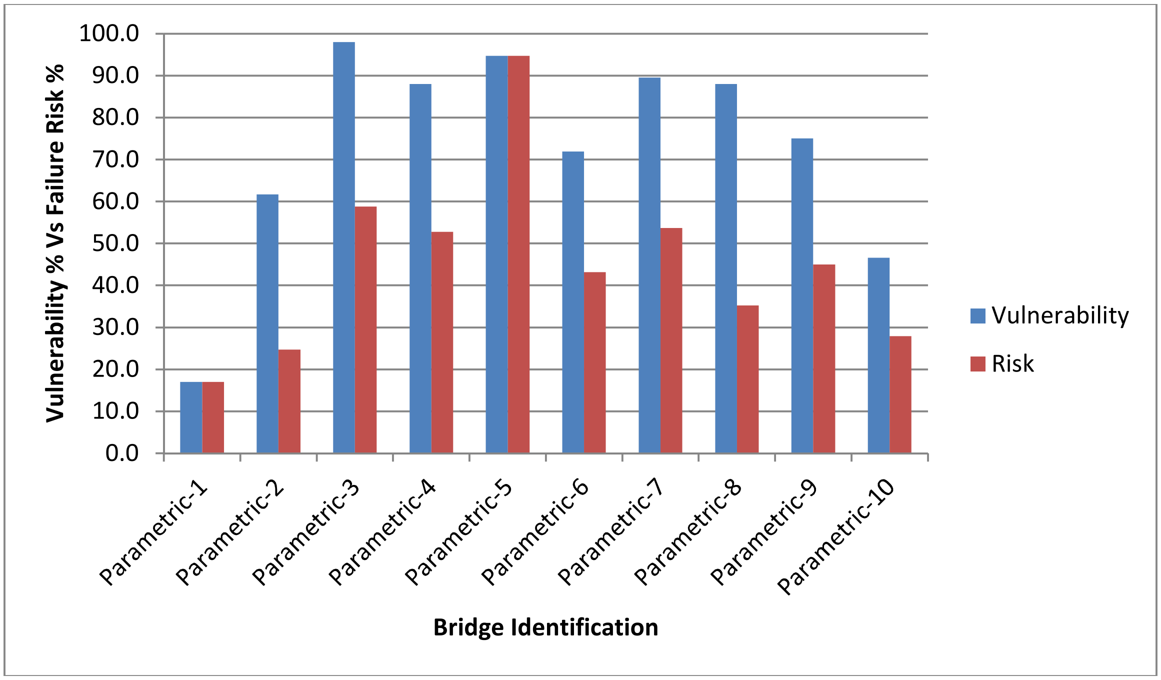


Fig. 6-3 Extreme Event Vulnerability Rating Vs Risk of Roads Network Disruption (Bridges #11 – to #20)

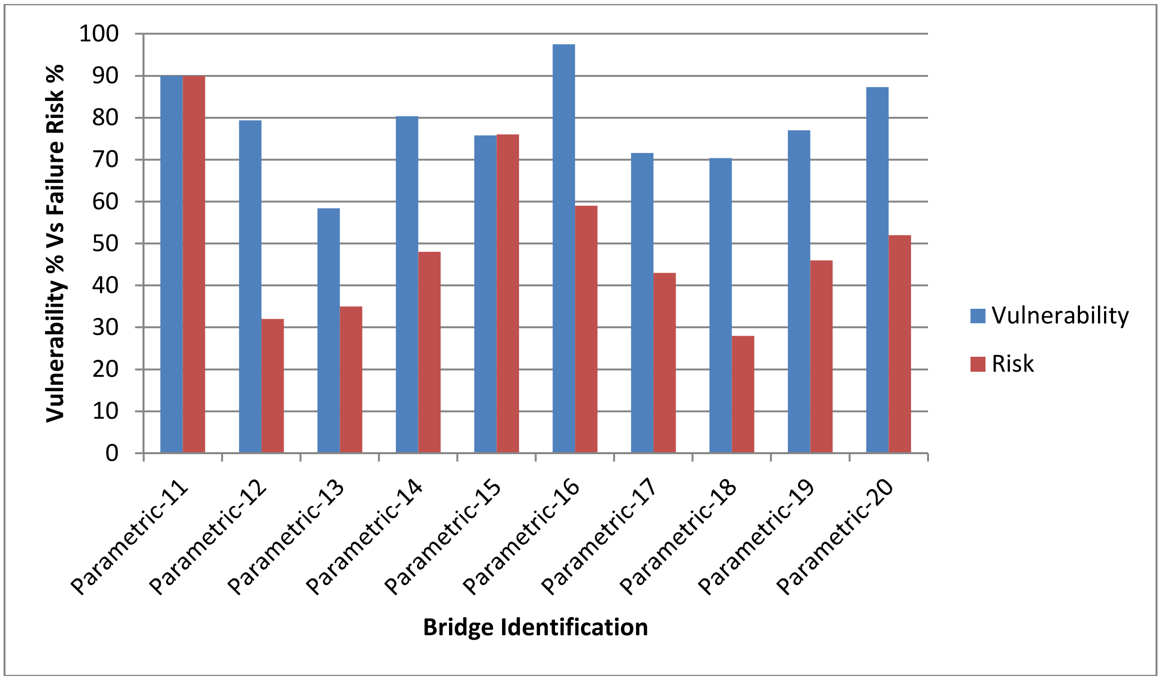


Fig. 6-4 Extreme Event Vulnerability Rating Vs Risk of Roads Network Disruption (Bridges #21 – to #30)

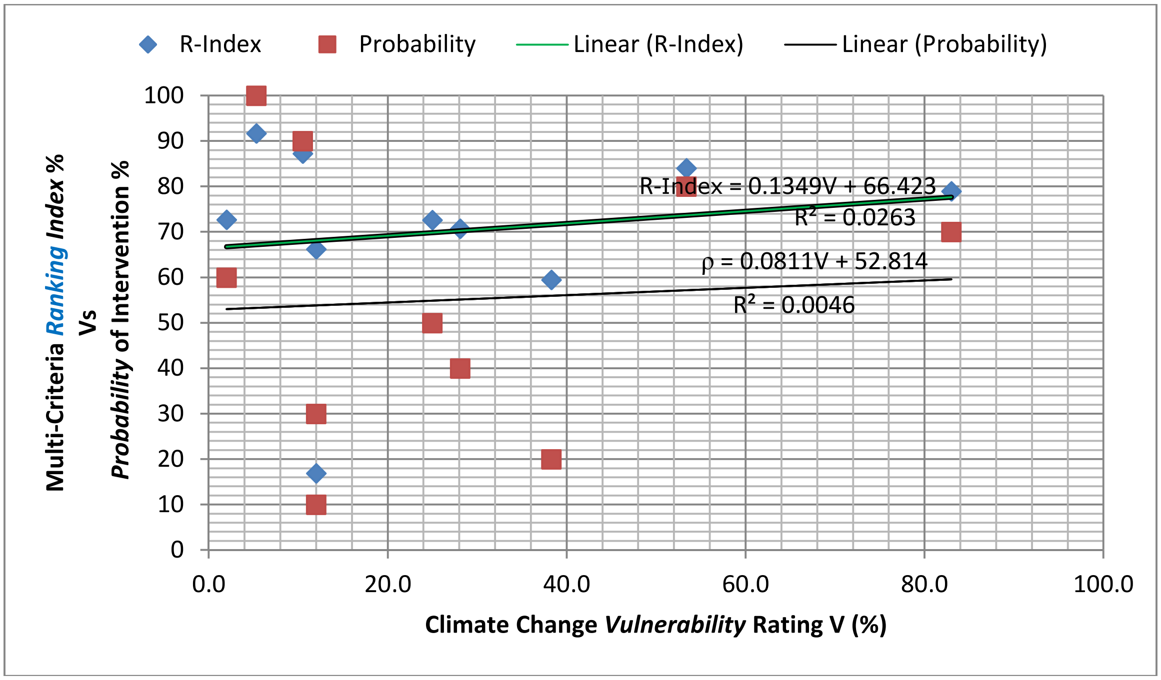


Fig. 6-5 Vulnerability Rating Vs Probability of Intervention and R-Index – Bridges 1 to 10

Ten of the 14 bridges studied in chapters 4 and 5 were candidates for rehabilitation work and these were chosen for the study of the new multi-criteria ranking method. For each of these 10 Bridges (Bridges #1 to 10), Fig. 6-5 shows the relationship between Climate Change Vulnerability and Multi-Criteria Ranking Index, on one hand, and Climate Change Vulnerability Vs the Probability ρ of being selected for intervention, on the other hand. The data for Fig. 6-5 come from Columns 1 to 5 of Table 6-7. The scatter in Fig. 6-5 is moderate ($R^2 = 0.0263$) for the Ranking Index but rather large ($R^2 = 0.0046$) for Probability of Intervention, and the reason for the latter is that the *vulnerability* rating of almost all 10 bridges is very low (the bridges are mostly very resilient) so that the final ranking (R-Index scores) of the bridges is governed by the other 2 criteria of bridge *performance* and *utility*. It follows that some bridges with low climate change vulnerability end up with a high probability of intervention where the high probability is dictated by the bridge's high score on one or both of the other 2 criteria. This is exactly how the multi-criteria selection and programming model for bridges is fashioned to work: each criterion is important enough to govern the intervention programming of one bridge ahead of other bridges.

Columns 6 to 10 of Table 6-7 show data for Climate Change Vulnerability V, Ranking Index (*R-Index)*, and the Probability P of Intervention for Bridges #11 to 20. Figure 6-7 shows plots of the relationships for Bridges #11 to 20. Again the scatter is minimal for *R-Index* and rather large for ρ. But this time the minimal scatter for *R-Index* is due to the fact that the high vulnerability ratings of most of the 10 bridges dictated/governed correspondingly high *R-Index* values so that, for the most part, a bridge with a low vulnerability rating does not come up with a higher *R-Index* score than a bridge with a high vulnerability rating, for example.

The large scatter in the Probability graph, on the other hand, is due to the fact that there are 5 bridges with *bunched-up* high Vulnerability scores in the narrow range of 88.0% to 94.7% (Column 7 of Table 6-7) and yet there is 40% probability separating the 1st-ranked and 5th-ranked of those bridges, thus pushing down the data points vertically by 40 points within that narrow spread of vulnerability rating. But the scatter is also due to the fact that there are only 10 bridges to be programmed so that the 1st-ranked and 2nd-ranked bridge, for example, are separated by 10% probability whereas they would be separated by only 1% probability if there were 100 bridges to be programmed. In the latter case, there would be only a 4% drop in probability of intervention between the 1st and 5th ranked bridges over a 6.7% spread of vulnerability, which indicates a very low level of scatter in the values.

Finally, data for Bridges #21 to 30 are shown in Columns 11 to 15 of Table 6-7 and plotted in Fig. 6-8. Similar to Fig. 6-7 for Bridges #11 to 20, Fig. 6-8 shows minimal scatter for *R-Index* but a larger scatter for probability of intervention ρ. With the rating of 5 bridges coming in between 80% and 97%, the reasons for these trends are the same as stated previously for Bridges 11 to 20 (Fig. 6-7). For Bridges #21 to 30, the association between the 3 quantities are the following (Fig. 6-8).

$$\text{R-Index} = 0.54V + 36.5 \qquad (6\text{-}12)$$

$$\rho = 1.28V - 45.9 \qquad (6\text{-}13)$$

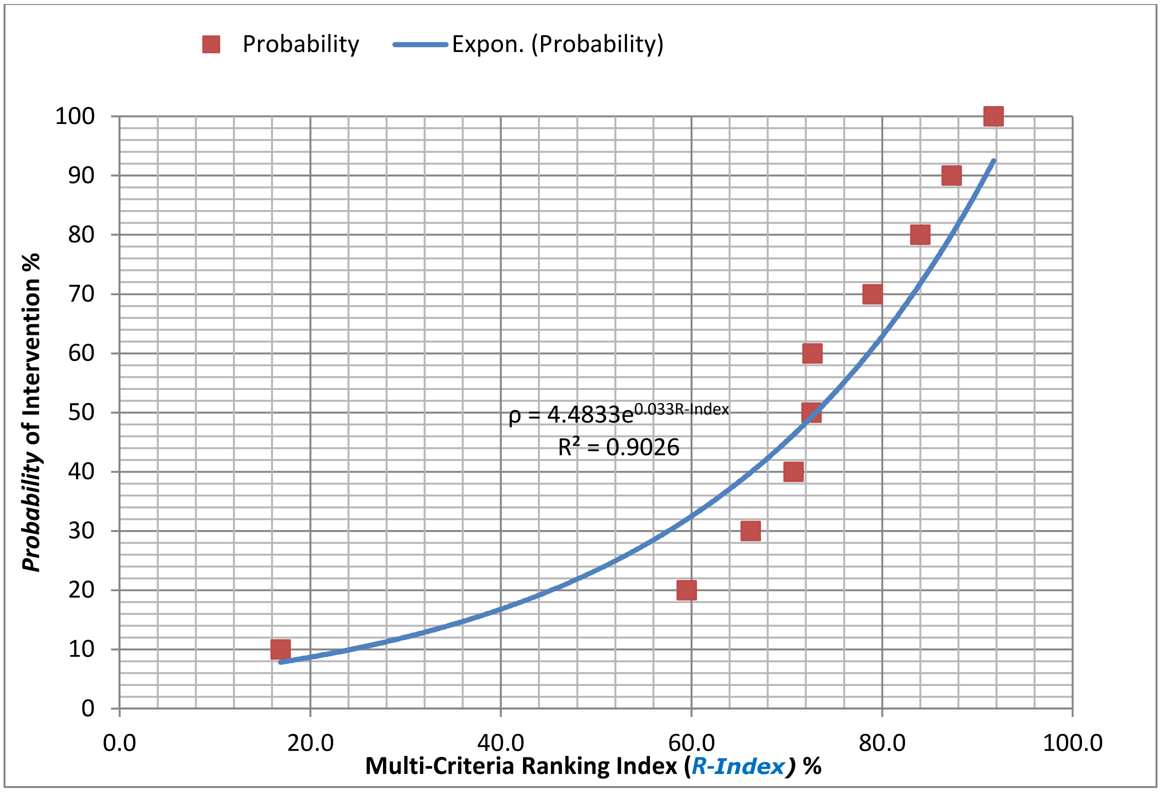


Fig. 6-6 Ranking Index Vs Probability of Intervention – Bridges 1 to 10

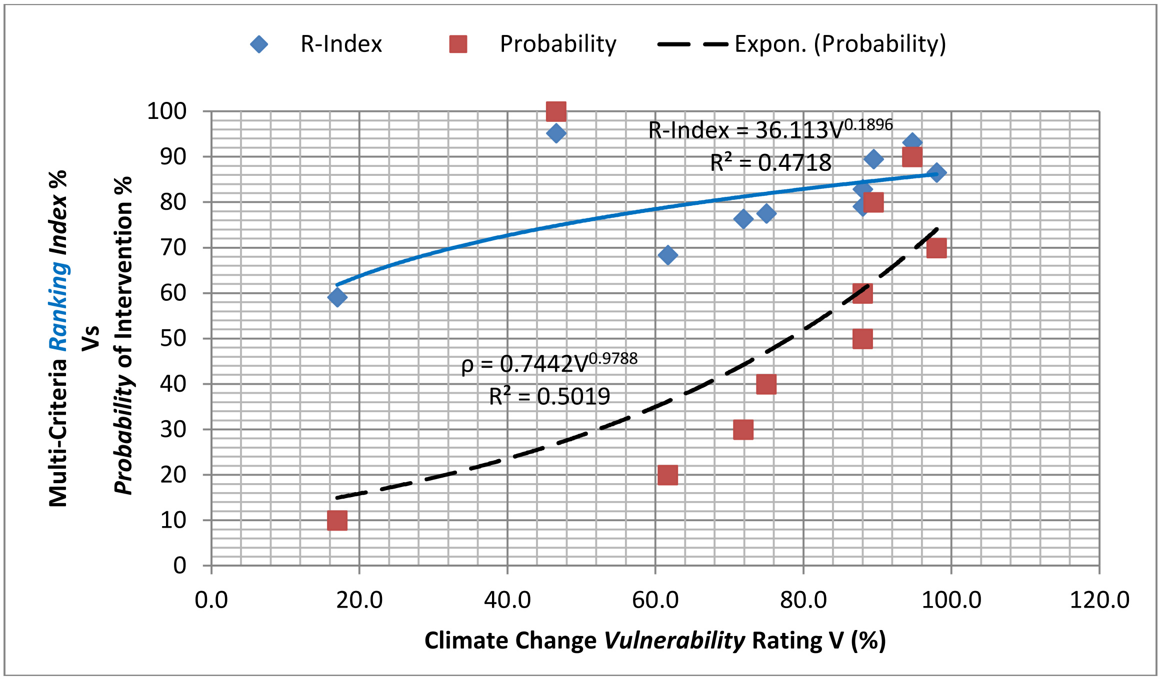


Fig. 6-7 Vulnerability Rating Vs Probability of Intervention and R-Index – Bridges 11 to 20

Table 6-7

Variation of *Probability of Intervention* with Climate Change *Vulnerability*

Bridge # 1	Extreme Event Vulnerability Rating V (%) 2	Ranking Index (%) 3	Ranking 4	Probability (%) 5	Bridge # 6	Extreme Event Vulnerability Rating V (%) 7	Ranking Index (%) 8	Ranking 9	Probability (%) 10	Bridge # 11	Extreme Event Vulnerability Rating V (%) 12	Ranking Index (%) 13	Ranking 14	Probability (%) 15
1	83.0	79.0	4	70	11	17.0	59.1	10	10	21	90.0	84.7	5	60
2	38.3	59.5	9	20	12	61.7	68.4	9	20	22	79.4	73.9	8	30
3	2.0	72.7	5	60	13	98.0	86.6	4	70	23	58.4	72.7	9	20
4	12.0	66.2	8	30	14	88.0	79.1	6	50	24	80.4	75.2	7	40
5	5.3	91.7	1	100	15	94.7	93.2	2	90	25	75.8	89.1	2	90
6	28.1	70.7	7	40	16	71.9	76.4	8	30	26	97.5	86.4	4	70
7	10.5	87.3	2	90	17	89.5	89.5	3	80	27	71.6	86.6	3	80
8	12.0	16.9	10	10	18	88.0	82.9	5	60	28	70.4	51.7	10	10
9	25.0	72.6	6	50	19	75.0	77.6	7	40	29	77.0	78.1	6	50
10	53.4	84.0	3	80	20	46.6	95.2	1	100	30	87.3	93.6	1	100

For all 30 bridges, the ranking results are presented in Table 6-9, and the relationship between the probability of intervention ρ and the ranking index (*R-Index)* is depicted in Fig. 6-9. With the 2 outlier projects (Bridge #20 with 42.8% score on *R-Index* and Bridge #30 with 31.9% score on *R-Index*) excluded, the correlation is very strong and the coefficient of determination is 0.98.

Table 6-8 Variation of *Ranking Index* with *Vulnerability* for Parametric Bridges #11 to 20

Bridge # 1	Performance % 2	Position 3	Percentile 4	Weight 5	Utility (%) 6	Position 7	Percentile 8	Weight 9	Extreme Event % 10	Position 11	Percentile 12	Weight 13	Σ(Weights) 14	Ranking Index 15	Governed By 16
11	19.3	9	0.1	0.02	65.0	8	0.2	0.14	90.0	2	0.8	0.83	1	84.7	V
12	27.1	7	0.3	0.07	77.4	4	0.6	0.42	79.4	5	0.5	0.42	1	73.9	V&Ut
13	73.1	4	0.6	0.60	72.2	6	0.4	0.40	58.4	10	0.0	0.00	1	72.7	BCI&Ut
14	73.0	5	0.5	0.41	67.0	7	0.3	0.23	80.4	4	0.6	0.46	1	75.2	All 3
15	27.4	6	0.4	0.10	100	1	0.9	0.83	75.8	7	0.3	0.18	1	89.1	Utility
16	74.4	3	0.7	0.31	80.0	3	0.7	0.34	97.5	1	0.9	0.45	1	86.4	V+
17	6.2	10	0.0	0.00	89.6	2	0.8	0.83	71.6	8	0.2	0.17	1	86.6	Utility
18	22.3	8	0.2	0.14	60.0	10	0.0	0.00	70.4	9	0.1	0.61	1	51.7	V+
19	80.0	2	0.8	0.46	75.7	5	0.5	0.27	77.0	6	0.4	0.23	1	78.1	V+
20	100	1	0.9	0.54	63.5	9	0.1	0.04	87.3	3	0.7	0.39	1	93.6	V&BCI

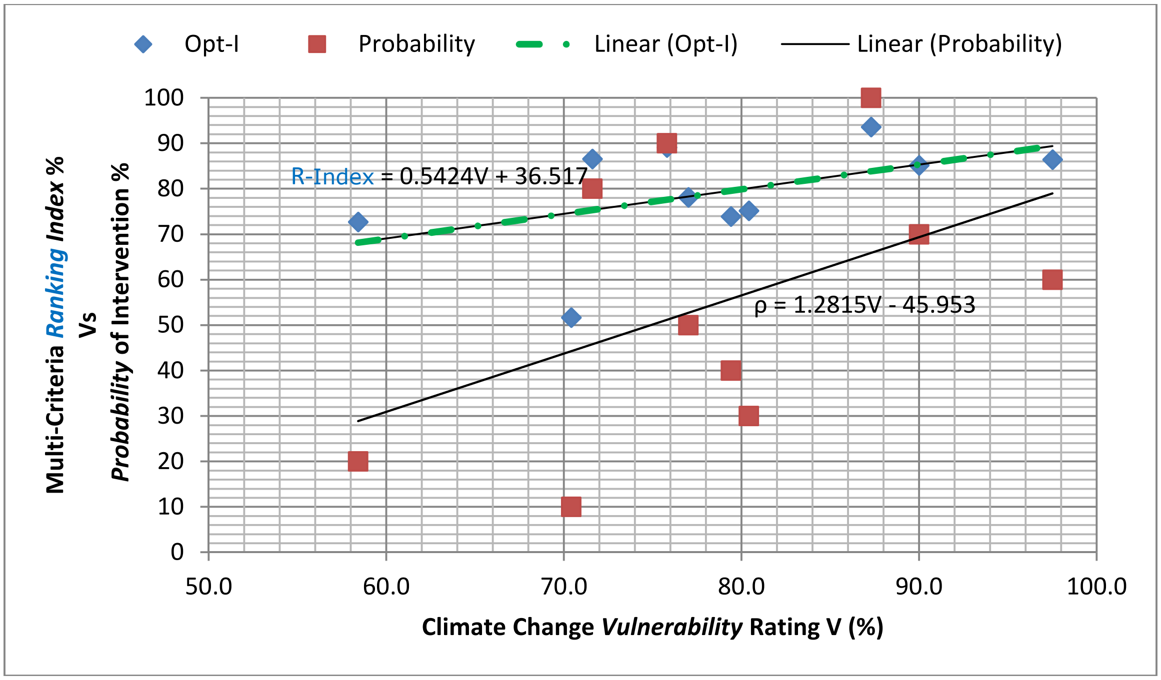


Fig. 6-8 Vulnerability Rating Vs Probability of Intervention and R-Index – Bridges 21 to 30

Table 6-9 Variation of *Probability of Intervention* with *Ranking Index* – 4 Criteria

Bridge #	Performance %	Ranking	Percentile	Weight	Utility (%)	Ranking	Percentile	Weight	Extreme Event %	Ranking	Percentile	Weight	Extreme Load %	Ranking	Percentile	Weight	Σ(Weights)	Ranking Index	Ranking	Probability
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
5	27.4	24	0.20	0.02	100.0	1	0.97	0.40	75.8	13	0.57	0.18	100	1	0.97	0.40	1	94.1	1	100.0
10	100.0	1	0.97	0.51	63.5	18	0.40	0.13	87.3	7	0.77	0.35	0	30	0.00	0.00	1	90.6	2	96.7
13	26.9	26	0.13	0.02	79.8	10	0.67	0.35	98.0	1	0.97	0.63	0	30	0.00	0.00	1	89.9	3	93.3
14	93.0	3	0.90	0.54	33.0	28	0.07	0.01	88.0	6	0.80	0.45	0	30	0.00	0.00	1	89.9	4	90.0
8	22.3	27	0.10	0.02	60.0	20	0.33	0.14	70.4	19	0.37	0.18	100	1	0.97	0.67	1	88.0	5	86.7
6	74.4	10	0.67	0.25	80.0	9	0.70	0.28	97.5	2	0.93	0.46	0	30	0.00	0.00	1	86.7	6	83.3
27	94.8	2	0.93	0.66	58.3	21	0.30	0.13	71.6	18	0.40	0.21	0	30	0.00	0.00	1	85.1	7	80.0
7	6.2	30	0.00	0.00	89.6	4	0.87	0.71	71.6	17	0.43	0.29	0	30	0.00	0.00	1	84.4	8	76.7
16	84.0	4	0.87	0.39	90.0	3	0.90	0.43	71.9	16	0.47	0.18	0	30	0.00	0.00	1	84.4	9	73.3
25	37.5	23	0.23	0.06	92.0	2	0.93	0.64	75.8	14	0.53	0.30	0	30	0.00	0.00	1	83.6	10	70.0
15	57.4	18	0.40	0.19	57.0	23	0.23	0.11	94.7	3	0.90	0.70	0	30	0.00	0.00	1	83.5	11	66.7
11	80.7	6	0.80	0.48	85.0	5	0.83	0.52	17.0	30	0.00	0.00	0	30	0.00	0.00	1	82.9	12	63.3
1	19.3	28	0.07	0.01	65.0	17	0.43	0.26	90.0	4	0.87	0.73	0	30	0.00	0.00	1	82.6	13	60.0
24	83.0	5	0.83	0.35	83.7	6	0.80	0.34	80.4	8	0.73	0.30	0	30	0.00	0.00	1	82.5	14	56.7
21	70.0	14	0.53	0.28	63.0	19	0.37	0.17	90.0	5	0.83	0.55	0	30	0.00	0.00	1	79.9	15	53.3
18	77.7	9	0.70	0.33	80.8	7	0.77	0.38	78.0	12	0.60	0.29	0	30	0.00	0.00	1	79.0	16	50.0
9	80.0	7	0.77	0.57	75.7	12	0.60	0.42	27.0	28	0.07	0.02	0	30	0.00	0.00	1	77.3	17	46.7
2	27.1	25	0.17	0.04	77.4	11	0.63	0.46	79.4	10	0.67	0.50	0	30	0.00	0.00	1	76.3	18	43.3
26	79.0	8	0.73	0.92	14.8	30	0.00	0.00	37.5	26	0.13	0.08	0	30	0.00	0.00	1	75.7	19	40.0
4	73.0	12	0.60	0.33	67.0	16	0.47	0.24	80.4	9	0.70	0.43	0	30	0.00	0.00	1	74.7	20	36.7
28	42.3	20	0.33	0.19	80.3	8	0.73	0.80	20.4	29	0.03	0.01	0	30	0.00	0.00	1	72.5	21	33.3
3	73.1	11	0.63	0.45	72.2	13	0.57	0.40	58.4	22	0.27	0.15	0	30	0.00	0.00	1	70.5	22	30.0
22	55.0	19	0.37	0.26	49.7	25	0.17	0.11	79.4	11	0.63	0.64	0	30	0.00	0.00	1	70.0	23	26.7
17	66.2	16	0.47	0.35	69.6	15	0.50	0.39	68.5	20	0.33	0.26	0	30	0.00	0.00	1	68.1	24	23.3
12	72.9	13	0.57	0.55	57.4	22	0.27	0.20	61.7	21	0.30	0.25	0	30	0.00	0.00	1	67.0	25	20.0
19	60.0	17	0.43	0.35	51.7	24	0.20	0.14	75.0	15	0.50	0.51	0	30	0.00	0.00	1	66.5	26	16.7
29	68.0	15	0.50	0.73	28.7	29	0.03	0.02	57.0	24	0.20	0.25	0	30	0.00	0.00	1	64.5	27	13.3
23	39.0	22	0.27	0.17	71.5	14	0.53	0.61	58.4	23	0.23	0.22	0	30	0.00	0.00	1	63.2	28	10.0
20	40.0	21	0.30	0.47	43.5	26	0.13	0.23	46.6	25	0.17	0.30	0	30	0.00	0.00	1	42.8	29	6.7
30	17.9	29	0.03	0.08	37.4	27	0.10	0.53	27.3	27	0.10	0.39	0	30	0.00	0.00	1	31.9	30	3.3

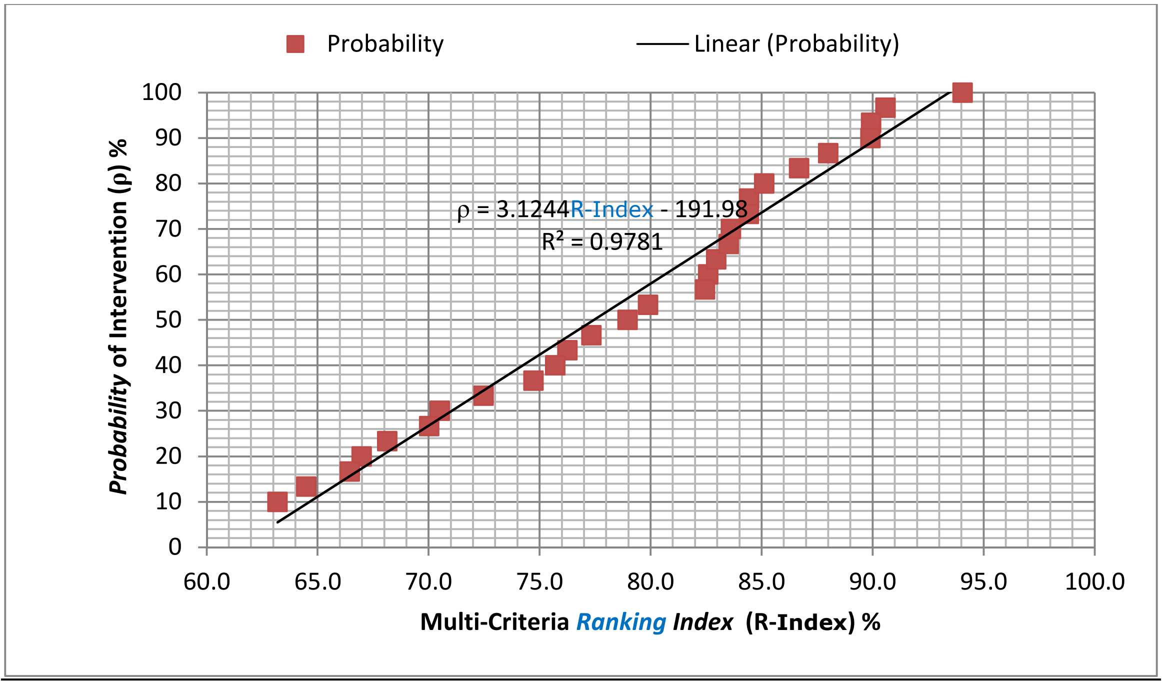


Fig. 6-9 Ranking Index Vs Probability of Intervention – ALL 30 Bridges & 4 Criteria

The relationship is of the form:

$$\rho = 3.124\mathit{R\text{-}Index} - 192 \qquad (6\text{-}14)$$

With those 2 projects included, the coefficient of determination is 0.79.

6.7. Performance of the Method

The contribution of each of the 4 criteria into the *Ranking Index* is shown in Fig. 6-10 for each project while the Map of the Roads Network showing the distribution within the jurisdiction of the 10 inventory bridges (Bridges # 1 to 10) is shown in Fig. 6-11. Table 6-9 shows that of all 30 bridges, Bridge #5 ranks 1st with 94.1% score on *R-Index* and does so by scoring 100% on each of *utility* (Agency Benefits, Column 6) and *extreme load vulnerability*, Column 14). It is inconsequential that Bridge #5 scored a low 27.4% on bridge performance (BCI, Column 2).

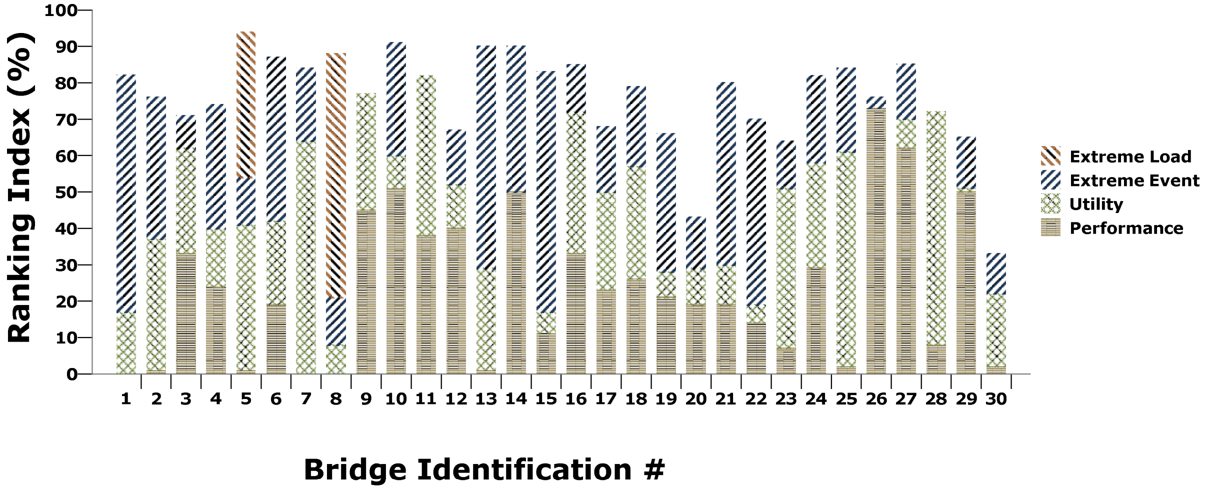


Fig. 6-10 Ranking Index (*R-Index*) Broken Down by Criteria

That's because, as contemplated in the proposed methodology, for a high *R-Index* score, it is sufficient that Bridge #5 scores 100% on any of the 4 criteria, because each criterion is deemed important enough to govern the implementation of Bridge Project #5 ahead of other bridge projects slated for implementation.

Similarly, Bridge #10 comes in 2^{nd}-ranked with 90.6% score on *R-Index*, made possible by its 100% score on *performance*, and notwithstanding its 0% (zero percent) score on *extreme loads* or its 63.5% score on *utility*. This characteristic is evident throughout Table 6-9 and Fig. 6-10, and they demonstrate that there is more than one *criterion-way* to get to the top. So, the method performs very much as intended.

The other important purpose of Fig. 6-10, however, is to illustrate that there is not any one criterion that is pre-determined as the most important. In other words, there is no subjectively determined hierarchy for the criteria or criteria weights. Fig. 6-10 shows that different criteria contribute the largest share to the ranking index of the different bridges. For example, climate vulnerability has the largest weight and largest contribution for Bridges #1, #13, #15, #19, #21, and #22, whereas it is bridge performance for Bridges #10, #26, and #27, etc.

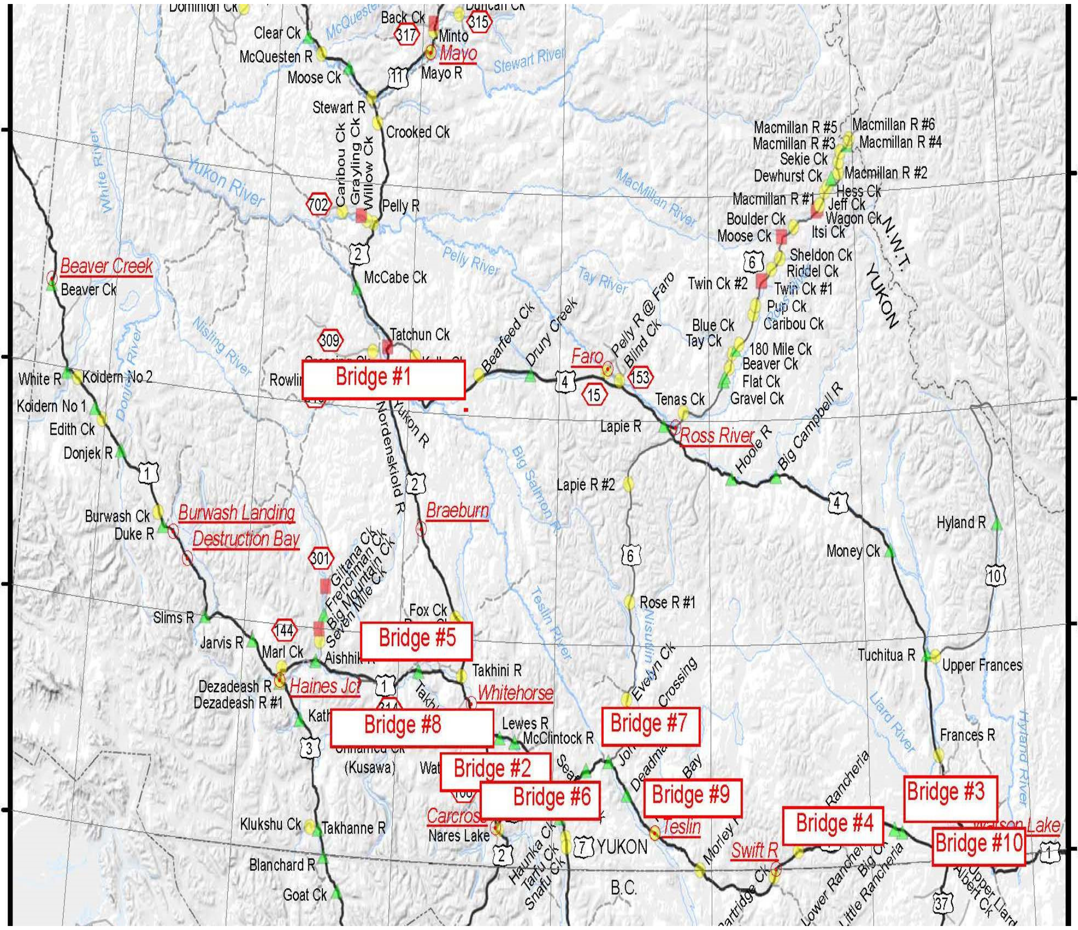


Fig. 6-11 Roads Network Map of the Studied Bridge Inventory

A comparison of the calculated weights in Table 6-9 (Columns 5, 9, 13, and 17) provides *verification* that for each of the 30 bridge projects, the highest rated criterion always attracted the largest weight and the lowest-rated criterion always attracted the smallest weight. The same also holds for the calculated weights listed in Table 6-3 (Columns 5, 9, and 13) and Table 7-2 (Columns 5, 9, 13, and 17), where the criterion with the largest product (rating times ranking) attracts the highest weight while the criterion with the smallest product attracts the lowest weight just as intended in the formulation of the weights. This *verifies* that the method performs as intended.

Fig. 6-12 depicts the risk evaluation matrix for highway bridges in the presence of both *time-dependent condition deterioration* and *climate-triggered extreme loads*. The goal is to move all highway bridges into the *minimal risk* condition as shown in Fig. 6-12. In practice, there is seldom enough money and it is seldom feasible to do this all at once, so that this is often undertaken over a planning horizon of 10 to 20 years or more. Figure 6-13 depicts the status of risk after, say, 50% of the total budget requirement has been applied to move the overall bridge inventory halfway from *significant risk* status to *minimal risk* status.

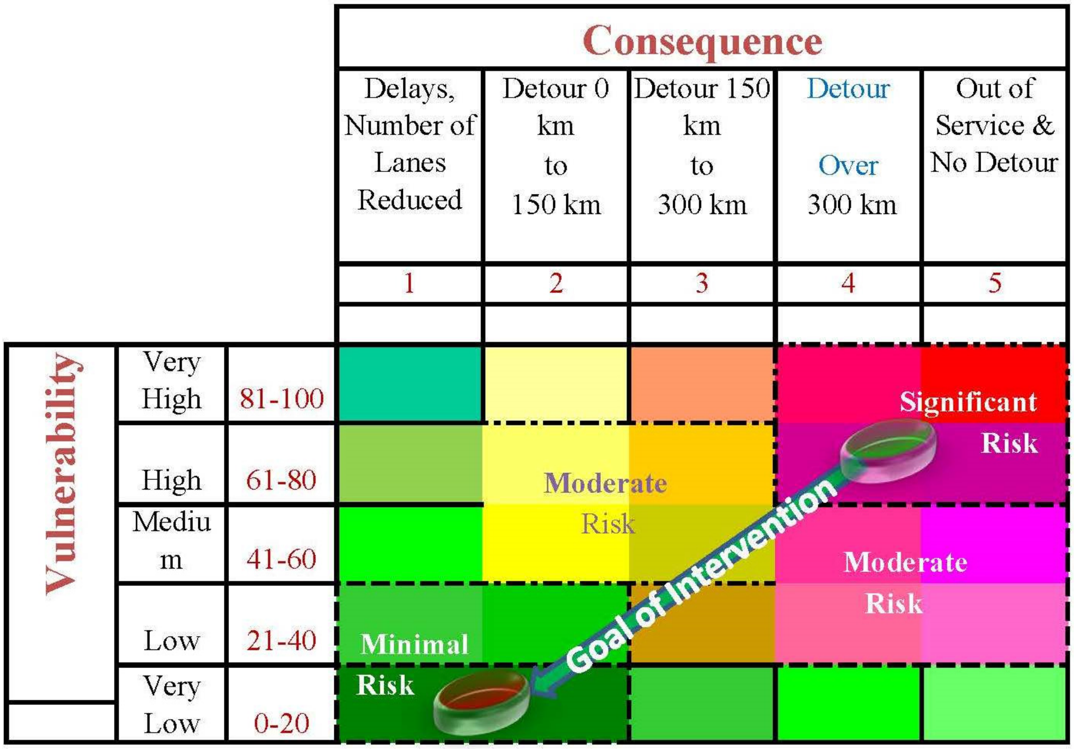


Fig. 6-12 Risk Management Matrix – Climate-triggered Extreme *Events* and Extreme *Loads*

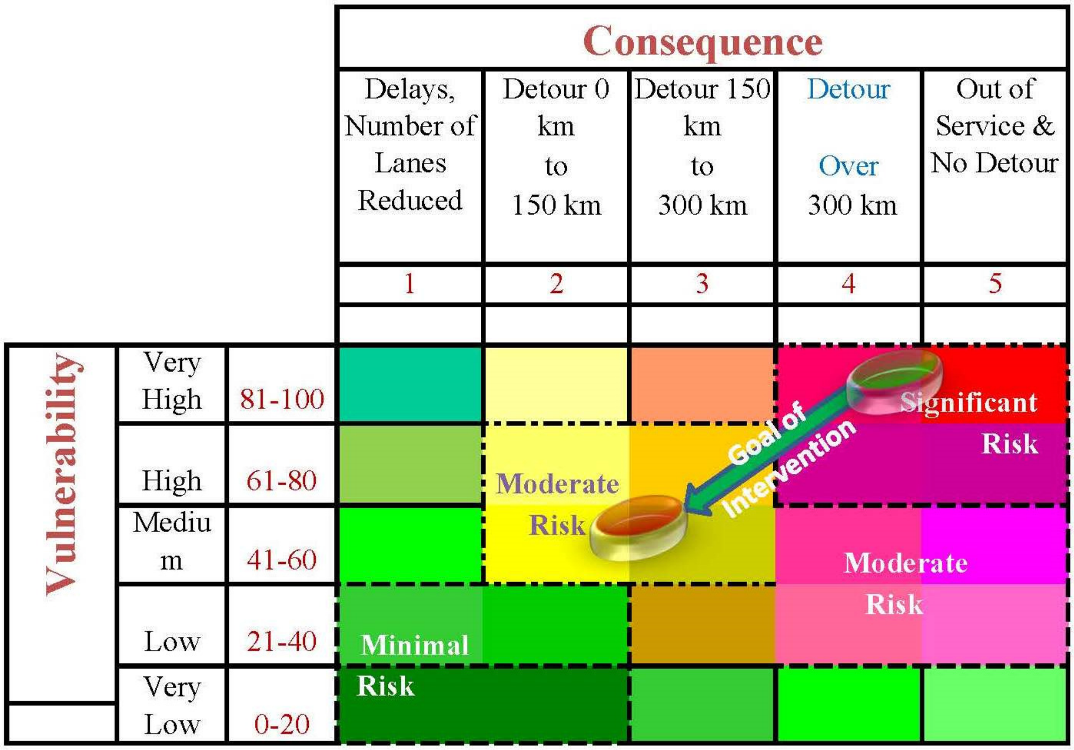


Fig. 6-13 Risk Management Matrix – Budget Constraint

6.8. Overall Model

The Flow Chart of Fig. 6-14 depicts the overall bridge management model comprising time-dependent deterioration, structural (extreme loads) and non-structural (extreme events) climate change vulnerability, where *climate-change preservation work* (e.g. raising the bridge to provide sufficient freeboard/hydraulic capacity) are to be undertaken simultaneously with *time-dependent deterioration preservation work* to minimize the cost of mobilization and demobilization. The model of Fig. 6-14, developed in this thesis, provides a logical and a ranking technique for determining the order of bridge projects' implementation with a view to reducing the risk of bridge failure or loss of service.

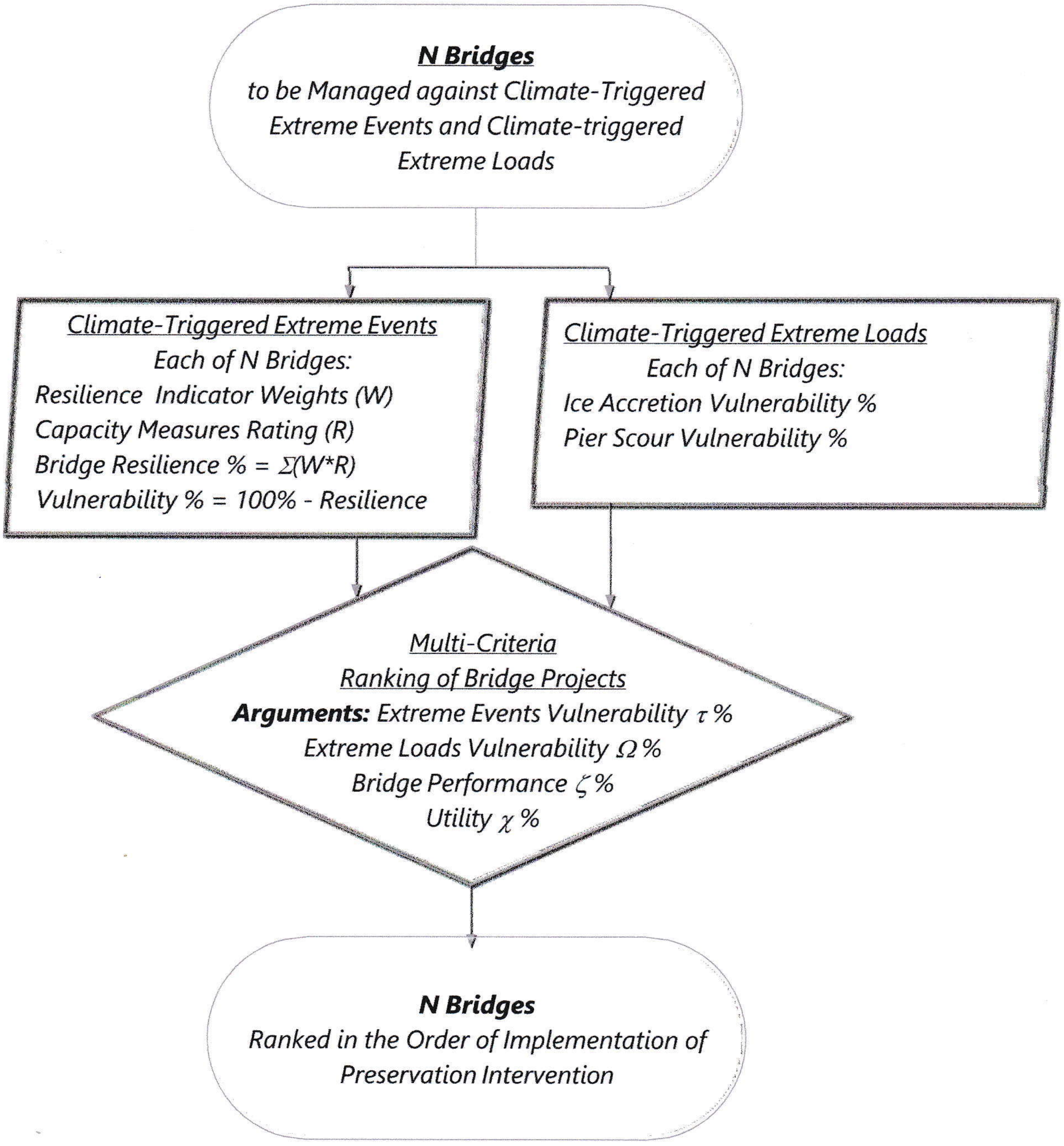


Fig. 6-14 Flow Chart – Managing Highway Bridges against Climate-Triggered Extreme *Events*, Climate-Triggered Extreme *Loads*, and Time-dependent Deterioration

6.9. Definition of Ranking and Prioritization

Based on the findings of this chapter, the following definition of ranking is derived: "Ranking *of bridge projects is defined as the ordering of projects' implementation determined by a weighted-criteria formulation in which the value function (the Ranking Index) is maximised via a criteria-weight scheme that assigns the largest weight to the highest-rated criterion and the least weight to the lowest-rated criterion*".

In comparison, a suitable definition for prioritization should be: "*Prioritization is a preference order for the implementation of competing alternative strategies or projects based on subjectively-established or expert-elicited ranking of a set of criteria*".

6.10. Summary

A non-iterative, one-directional method for the ranking of bridge projects implementation based on multiple criteria has been proposed and demonstrated here for a sample inventory of ten real bridges and 20 parametric bridges, which are ranked on four criteria, namely, bridge performance, utility, vulnerability to climate-triggered extreme events, and vulnerability to climate-triggered extreme loads. Based on the review of the existing methods and the results of the present study, the following conclusions have been derived.

- The proposed method clearly separates the concept of *prioritization* from the concept of *ranking* and does so by avoiding the subjective promotion of any one criterion over another, which eliminates tradeoffs from the value function formulation.
- Using the new method presented in this chapter, bridge projects forming a part of an inventory-wide intervention program can be rapidly ranked to reflect the costs and benefits to the transportation agency, bridge performance enhancement (i.e. improvement of the bridge condition index), the risks posed by climate-triggered extreme events, and the risks posed by climate-triggered extreme loads.

- By using *weights* derived from the criteria rating, iteration is eliminated in the selection of projects using the proposed method, and the computer run time is significantly reduced as compared to that in traditional ranking methods.
- The method provides for an objective *rating* of each bridge project against the various ranking criteria, while accounting for such intrinsic attributes of the bridge/project as the bridge rehabilitation cost, the bridge performance prior to intervention, the bridge performance following intervention, cost savings per dollar spent on the intervention, bridge clearance above the 100-year flood elevation, ice accretion extreme load, availability and length of detour routes, etc.
- The proposed method is expected to rapidly rank projects for any size of inventory because it is a one-direction procedure, with no cycles to repeat.
- The ranking criteria to be used with this method should be limited to only those criteria that the transportation agency considers to be each important enough to govern the decision to program a bridge project ahead of other bridge projects slated for implementation. Bridge performance, utility, climate-triggered extreme loads, and climate-triggered extreme events are proposed as meeting that condition.

Finally, it should be noted that, under budget constraint, the proposed method does – in one fell swoop – select projects for implementation such that not only those projects that produce the highest overall *inventory performance* per dollar spent are programmed early, but also those projects that serve to negate *vulnerability to sudden bridge failure occasioned by climate-triggered extreme events* as well as projects that attract the highest non-performance *benefits* for tax payers.

Chapter 7

Comparison of the Multi-Criteria Ranking Method with the Analytic Hierarchy Process (AHP)

7.1. Introduction

The Analytic Hierarchy Process (AHP) was first proposed by Saaty (2001) for criteria weight calculation in multi-criteria decision making (MCDM). It calculates the weights to be assigned to the various criteria based on expert elicitation of criteria ranking, on one hand, and the analytic hierarchy formulation proposed by Saaty (2001), on the other hand. The method appears most suited to decision problems in which the top choice is all that's important, and problems in which the losing alternatives can be discarded without any negative consequences. An example of such problems would be deciding on what full-size car to buy given the alternatives of the Toyota Camry, Nissan Altima, Honda Accord, and Hyundai Sonata, which are to be ranked based on cost, style, fuel economy, roominess, and second-hand value. This researcher has not found an instance of the application of the AHP method in optimization of bridge projects selection where the goal is to select a mix of projects that rate high on *any one* or more of the criteria. The AHP is explored here to determine its applicability as a simpler alternative method for bridge project selection, and to compare it to the new ranking method developed in this thesis.

If a bridge project scored 95% on extreme events vulnerability and 0% on each of the other three criteria presented in chapter 6, the proposed ranking method would still select the said project near the very top of the thirty bridges, and the calculated ranking index (R-Index) would be close to 95%. In comparison, AHP would probably place that project near the bottom of 30 bridges (with a weight of 0.30 or so for the said extreme events vulnerability criterion).

In this chapter, the AHP and the new ranking method are critically compared by evaluating their performance in specified scenarios, by identifying the type of problems for which they are each better suited, and by applying the optimization test: does the method *maximize* the value function (i.e. by comparing the totals of the AHP Prioritization Indices and the Ranking Indices for the 30 bridges).

7.2. Selection Efficacy

For this study, the AHP weights were established via expert elicitation obtained using questionnaire distributed to the heads of bridge engineering in the provinces and territories of Canada as well as technical committee members of the Canadian Highway Bridge Design Code. The weights established by applying the AHP were: bridge performance 0.334, utility 0.309, extreme event vulnerability 0.162, and extreme load vulnerability 0.189.

For the 30 bridges considered in Chapter 6, Table 7-1 shows that the top 10 bridges selected for intervention, based on the above-cited AHP weights, are Bridges #5, #16, #10, #24, #6, #18, #27, #4, #21, and #3. This compares with Bridges #5, #10, #13, #14, #8, #6, #27, #7, #16, and #25 selected by the new ranking method (Table 6-9 of Chapter 6). These two rankings of the 10 top bridges by each method show that AHP misses Bridge #8, which scores 100% on extreme loads vulnerability, and yet doesn't place in the top 10 of the AHP rankings. Also missed are Bridge #14 with 93% score on bridge performance, Bridges #25 and #7 with 92% and 89.6% score, respectively, on utility, Bridges #15, #13 and #1 with 94.7%, 98%, and 90%, respectively, on extreme events vulnerability. All of these seven bridges are in need of urgent attention, and the transportation agency can't afford to have them escape through the cracks. In contrast, the new ranking method (Table 6-9) misses only Bridge #15 in the top 10. Even so, the new method performs much better than the AHP, as Bridge #15 comes in 11th for the new method compared to 18th for the AHP.

Table 7-1 AHP Prioritization of Bridge Projects' Selection – 30 Bridges of Chapter 6

Bridge #	Bridge % Performance	Weight	Utility (%)	Weight	Extreme Event Vulnerability %	Weight	Extreme Load Vulnerability %	Weight	Σ(Weights)	AHP Index	Ranking
1	2	5	6	9	10	13	14	17	18	19	20
5	27.4	0.34	100.0	0.309	75.8	0.162	100	0.189	1	71.4	1
16	84.0	0.34	90.0	0.309	71.9	0.162	0	0.189	1	68.0	2
10	100.0	0.34	63.5	0.309	87.3	0.162	0	0.189	1	67.7	3
24	83.0	0.34	83.7	0.309	80.4	0.162	0	0.189	1	67.1	4
6	74.4	0.34	80.0	0.309	97.5	0.162	0	0.189	1	65.8	5
18	77.7	0.34	80.8	0.309	78.0	0.162	0	0.189	1	64.0	6
27	94.8	0.34	58.3	0.309	71.6	0.162	0	0.189	1	61.8	7
4	73.0	0.34	67.0	0.309	80.4	0.162	0	0.189	1	58.5	8
21	70.0	0.34	63.0	0.309	90.0	0.162	0	0.189	1	57.8	9
3	73.1	0.34	72.2	0.309	58.4	0.162	0	0.189	1	56.6	10
8	22.3	0.34	60.0	0.309	70.4	0.162	100	0.189	1	56.5	11
11	80.7	0.34	85.0	0.309	17.0	0.162	0	0.189	1	56.4	12
14	93.0	0.34	33.0	0.309	88.0	0.162	0	0.189	1	56.0	13
17	66.2	0.34	69.6	0.309	68.5	0.162	0	0.189	1	55.1	14
9	80.0	0.34	75.7	0.309	27.0	0.162	0	0.189	1	54.9	15
25	37.5	0.34	92.0	0.309	75.8	0.162	0	0.189	1	53.5	16
12	72.9	0.34	57.4	0.309	61.7	0.162	0	0.189	1	52.5	17
15	57.4	0.34	57.0	0.309	94.7	0.162	0	0.189	1	52.5	18
13	26.9	0.34	79.8	0.309	98.0	0.162	0	0.189	1	49.7	19
19	60.0	0.34	51.7	0.309	75.0	0.162	0	0.189	1	48.5	20
22	55.0	0.34	49.7	0.309	79.4	0.162	0	0.189	1	46.9	21
2	27.1	0.34	77.4	0.309	79.4	0.162	0	0.189	1	46	22
23	39.0	0.34	71.5	0.309	58.4	0.162	0	0.189	1	44.8	23
28	42.3	0.34	80.3	0.309	20.4	0.162	0	0.189	1	42.5	24
7	6.2	0.34	89.6	0.309	71.6	0.162	0	0.189	1	41.4	25
1	19.3	0.34	65.0	0.309	90.0	0.162	0	0.189	1	41.2	26
29	68.0	0.34	28.7	0.309	57.0	0.162	0	0.189	1	41.2	27
26	79.0	0.34	14.8	0.309	37.5	0.162	0	0.189	1	37.5	28
20	40.0	0.34	43.5	0.309	46.6	0.162	0	0.189	1	34.6	29
30	17.9	0.34	37.4	0.309	27.3	0.162	0	0.189	1	22.1	30
Total										**1572**	

7.3. Maximization of the Value Function

By definition, optimization should result in maximization of the value function. In the case where the rating of the various strategy alternatives (bridge projects) is on a scale of 100%, with a score of 100% corresponding to "*a dire need for immediate intervention*", the overall selection formulation should not diminish the value function relative to the criteria rating. In other words, a bridge project that scores 100% on extreme load vulnerability should not end up with a lowly overall score of 40% after the other criteria have been taken into account. It follows that since the higher a project rates on a criterion, the greater the intervention need and urgency, the value function must maximize the overall rating of such a project so that the need and urgency continue to be visible.

To study the performance of the new method on the maximization requirement, nine schedules of criteria weight (including the weight schedule determined using the AHP/survey in Chapter 3) for the four criteria considered in this study were applied to another set of thirty bridges (hereinafter called *the inventory of Chapter 7*). The performance of each of the nine weight schedules was then compared with the performance of the new ranking method. (Note: *The inventory of Chapter 7* is derived from the 30 bridges presented in Chapter 6 [see Table 7-1] by replacing the zero ratings of 28 of the 30 bridges on the criterion of *extreme load vulnerability* with non-zero ratings).

Table 7-2 shows the new method's ranking of the thirty bridges on the 4 criteria of bridge performance, utility, extreme event vulnerability, and extreme load vulnerability. The corresponding ranking using the AHP is shown in Table 7-3 based on the following criteria weights established by expert elicitation:

Bridge performance	0.339297
Utility	0.30946
Extreme events vulnerability	0.161962
Extreme loads vulnerability	0.189282

Table 7-2 (new ranking method) shows that the largest weight for bridge performance is 0.59 (Bridge #26), it is 0.68 (Bridge #7) for utility, 0.70 (Bridge #1) for extreme event vulnerability, and 0.92 (Bridge #30) for extreme load vulnerability. By comparison and unlike the new ranking method developed in this thesis, where the weights vary across criteria and across projects, AHP weights are fixed across the projects. Accordingly, Table 7-3 shows that there are only 4 weights for the entire AHP solution: 0.34 for bridge performance for all 30 bridges, 0.309 for utility, 0.162 for extreme event vulnerability, and 0.189 for extreme load vulnerability.

A comparison of Column 19 of Table 7-2 and Column 10 of Table 7-3 shows that the Ranking Index (Table 7-2) is larger for each of 30 bridges than the corresponding AHP Prioritization Index (Table 7-3). Further, the sum of all 30 indices is greater for the new method (Total: 2,348) than the AHP prioritization (Total: 1,908). Finally, Table 7-4 shows the AHP Prioritization Index for the full range of possible AHP weight schedules (a total of 9 schedules). The said AHP indices are expressed as a ratio of the Ranking Index for the 30 bridges. The highest ratio achieved by the AHP is 0.82 (82% of R-Index), which confirms the superiority of the new ranking formulation over the AHP formulation. All nine (9) ratios are plotted in Figure 7-1, and the plot shows that for the inventory data of Table 7-3, the value function (AHP Index) *totals* decline as the largest criterion weight increases from 0.25 to 1.0). It should be noted that in all 9 cases, *bridge performance* was chosen to be the largest-weighted criterion. Finally, the correlation between the weight schedule and the AHP Index is very strong, and takes the form:

$AHP = -\,0.1053 Weight + 0.8443$

The coefficient of determination is very high, at 0.9972.

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Table 7-2 Maximization of the Value Function – Multi-Criteria Ranking Method (4 Criteria)

Bridge #	Bridge Performance %	Ranking	Percentile	Weight	Utility %	Ranking	Percentile	Weight	Extreme Event Vulnerability %	Ranking	Percentile	Weight	Extreme Load Vulnerability %	Ranking	Percentile	Weight	Σ(Weights)	Ranking Index
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1	19.3	28	0.07	0.01	65.0	17	0.43	0.25	90.0	4	0.87	0.70	33	27	0.10	0.03	1	81.1
2	27.1	25	0.17	0.04	77.4	11	0.63	0.45	79.4	10	0.67	0.49	27	28	0.07	0.02	1	75.4
3	73.1	11	0.63	0.45	72.2	13	0.57	0.40	58.4	22	0.27	0.15	14	30	0.00	0.00	1	70.5
4	73.0	12	0.60	0.28	67.0	16	0.47	0.20	80.4	9	0.70	0.36	63	18	0.40	0.16	1	72.8
5	27.4	24	0.20	0.02	100.0	1	0.97	0.40	75.8	13	0.57	0.18	100	1	0.97	0.40	1	94.1
6	74.4	10	0.67	0.24	80.0	9	0.70	0.28	97.5	2	0.93	0.45	39	25	0.17	0.03	1	85.2
7	6.2	30	0.00	0.00	89.6	4	0.87	0.68	71.6	17	0.43	0.27	35	26	0.13	0.04	1	82.4
8	22.3	27	0.10	0.02	60.0	20	0.33	0.14	70.4	19	0.37	0.18	100	1	0.97	0.67	1	88.0
9	80.0	7	0.77	0.52	75.7	12	0.60	0.39	27.0	28	0.07	0.02	45	24	0.20	0.08	1	74.9
10	100.0	1	0.97	0.47	63.5	18	0.40	0.12	87.3	7	0.77	0.32	57	21	0.30	0.08	1	87.8
11	80.7	6	0.80	0.39	85.0	5	0.83	0.43	17.0	30	0.00	0.00	65	16	0.47	0.18	1	79.7
12	72.9	13	0.57	0.30	57.4	22	0.27	0.11	61.7	21	0.30	0.13	85	8	0.73	0.45	1	75.2
13	26.9	26	0.13	0.02	79.8	10	0.67	0.31	98.0	1	0.97	0.55	58	20	0.33	0.11	1	86.3
14	93.0	3	0.90	0.41	33.0	28	0.07	0.01	88.0	6	0.80	0.34	79	11	0.63	0.24	1	87.2
15	57.4	18	0.40	0.13	57.0	23	0.23	0.08	94.7	3	0.90	0.48	82	10	0.67	0.31	1	83.0
16	84.0	4	0.87	0.29	90.0	3	0.90	0.32	71.9	16	0.47	0.13	87	7	0.77	0.26	1	85.2
17	66.2	16	0.47	0.17	69.6	15	0.50	0.20	68.5	20	0.33	0.13	98	3	0.90	0.50	1	83.0
18	77.7	9	0.70	0.23	80.8	7	0.77	0.27	78.0	12	0.60	0.20	88	6	0.80	0.30	1	81.7
19	60.0	17	0.43	0.30	51.7	24	0.20	0.12	75.0	15	0.50	0.43	51	22	0.27	0.16	1	64.1
20	40.0	21	0.30	0.44	43.5	26	0.13	0.21	46.6	25	0.17	0.28	27	28	0.07	0.07	1	41.8
21	70.0	14	0.53	0.21	63.0	19	0.37	0.13	90.0	5	0.83	0.41	77	12	0.60	0.25	1	79.1
22	55.0	19	0.37	0.22	49.7	25	0.17	0.09	79.4	11	0.63	0.56	47	23	0.23	0.12	1	67.2
23	39.0	22	0.27	0.12	71.5	14	0.53	0.45	58.4	23	0.23	0.16	60	19	0.37	0.26	1	62.4
24	83.0	5	0.83	0.29	83.7	6	0.80	0.28	80.4	8	0.73	0.24	77	12	0.60	0.19	1	81.4
25	37.5	23	0.23	0.04	92.0	2	0.93	0.41	75.8	14	0.53	0.19	90	5	0.83	0.36	1	85.9
26	79.0	8	0.73	0.59	14.8	30	0.00	0.00	37.5	26	0.13	0.05	70	15	0.50	0.36	1	73.7
27	94.8	2	0.93	0.51	58.3	21	0.30	0.10	71.6	18	0.40	0.16	75	14	0.53	0.23	1	82.8
28	42.3	20	0.33	0.14	80.3	8	0.73	0.57	20.4	29	0.03	0.01	65	16	0.47	0.29	1	70.3
29	68.0	15	0.50	0.31	28.7	29	0.03	0.01	57.0	24	0.20	0.10	85	8	0.73	0.57	1	76.2
30	17.9	29	0.03	0.01	37.4	27	0.10	0.04	27.3	27	0.10	0.03	95	4	0.87	0.92	1	90.0
Total																		**2348**

7.4. Correlation between the Value Function and Each Criterion

For the 30 bridges of Chapter 6, Figure 7-3 shows the relationship between the bridge performance rating and the AHP Prioritization Index, on one hand, and the relationship between the bridge performance rating and the Ranking Index, on the other hand. The plot includes only those bridges that rated 80% or higher on the performance index criterion, chosen to demonstrate which method captures better the need for preservation intervention as indicated by a high criterion rating. The Figure shows that the R-Index values (the value function) are consistently higher than the AHP Prioritization Index by about 20%, which demonstrates that the new method does maximize the value function. Equally significant, the coefficient of determination between the ranking index and the bridge performance rating is 700% higher (0.72 versus 0.09) than the coefficient of determination between the AHP Prioritization Index and the bridge performance rating.

The relationship between the utility criterion rating and the AHP Prioritization Index is depicted in Figure 7-4, alongside the corresponding relationship for the new ranking method. Again, the plot includes only those bridges that rate 80% or higher on the utility criterion. Similar to what was found for the bridge performance criterion, the utility plot of Figure 7-4 shows that, by a margin of about 20%, the R-Index values are consistently higher than the AHP prioritization Index. The coefficient of determination is 1,100% higher for the new ranking method than the AHP.

Table 7-3 Maximization of the Value Function – *AHP Prioritization* – 30 Bridges and 4 Criteria

Bridge #	Bridge Performance %	Weight	Utility (%)	Weight	Extreme Event Vulnerability %	Weight	Extreme Load Vulnerability %	Weight	Σ(Weights)	Prioritization Index	Ranking
1	2	3	4	5	6	7	7	8	9	10	11
1	19.3	0.34	65.0	0.309	90.0	0.162	33	0.189	1	47.5	28
2	27.1	0.34	77.4	0.309	79.4	0.162	27	0.189	1	51	25
3	73.1	0.34	72.2	0.309	58.4	0.162	14	0.189	1	59.2	18
4	73.0	0.34	67.0	0.309	80.4	0.162	63	0.189	1	70.4	12
5	27.4	0.34	100.0	0.309	75.8	0.162	100	0.189	1	71.4	9
6	74.4	0.34	80.0	0.309	97.5	0.162	39	0.189	1	73.2	7
7	6.2	0.34	89.6	0.309	71.6	0.162	35	0.189	1	48.0	27
8	22.3	0.34	60.0	0.309	70.4	0.162	100	0.189	1	56.5	21
9	80.0	0.34	75.7	0.309	27.0	0.162	45	0.189	1	63.5	16
10	100.0	0.34	63.5	0.309	87.3	0.162	57	0.189	1	78.5	4
11	80.7	0.34	85.0	0.309	17.0	0.162	65	0.189	1	68.7	13
12	72.9	0.34	57.4	0.309	61.7	0.162	85	0.189	1	68.6	14
13	26.9	0.34	79.8	0.309	98.0	0.162	58	0.189	1	60.7	17
14	93.0	0.34	33.0	0.309	88.0	0.162	79	0.189	1	70.9	10
15	57.4	0.34	57.0	0.309	94.7	0.162	82	0.189	1	68.0	15
16	84.0	0.34	90.0	0.309	71.9	0.162	87	0.189	1	84.5	1
17	66.2	0.34	69.6	0.309	68.5	0.162	98	0.189	1	73.6	6
18	77.7	0.34	80.8	0.309	78.0	0.162	88	0.189	1	80.7	3
19	60.0	0.34	51.7	0.309	75.0	0.162	51	0.189	1	58.2	19
20	40.0	0.34	43.5	0.309	46.6	0.162	27	0.189	1	39.7	30
21	70.0	0.34	63.0	0.309	90.0	0.162	77	0.189	1	72.4	8
22	55.0	0.34	49.7	0.309	79.4	0.162	47	0.189	1	55.8	23
23	39.0	0.34	71.5	0.309	58.4	0.162	60	0.189	1	56.2	22
24	83.0	0.34	83.7	0.309	80.4	0.162	77	0.189	1	81.7	2
25	37.5	0.34	92.0	0.309	75.8	0.162	90	0.189	1	70.5	11
26	79.0	0.34	14.8	0.309	37.5	0.162	70	0.189	1	50.7	26
27	94.8	0.34	58.3	0.309	71.6	0.162	75	0.189	1	76.0	5
28	42.3	0.34	80.3	0.309	20.4	0.162	65	0.189	1	54.8	24
29	68.0	0.34	28.7	0.309	57.0	0.162	85	0.189	1	57.3	20
30	17.9	0.34	37.4	0.309	27.3	0.162	95	0.189	1	40.1	29
Total										**1908**	

Table 7-4 Maximization of the Value Function – AHP Vs Ranking Method

(*Bridge Performance as Largest-Weighted Criterion*)

	AHP Weights				Value Function Totals (AHP)	Ratio of R-Index Totals
	Performance	Utility	Extreme Events	Extreme Loads		
1	**0.25**	0.25	0.25	0.25	1933	0.82
2	***0.334***	*0.309*	*0.162*	*0.189*	*1,908*	*0.81*
3	**0.40**	0.3	0.15	0.15	1894	0.80
4	**0.50**	0.25	0.15	0.10	1,871	0.79
5	**0.60**	0.20	0.10	0.10	1845	0.78
6	**0.70**	0.10	0.10	0.10	1822	0.77
7	**0.80**	0.20	0.0	0.0	1786	0.76
8	**0.90**	0.10	0.0	0.0	1771	0.75
9	**1.0**	0.0	0.0	0.0	1748	0.74

R-Index Total: 2,348 (Table 7-2)

The relationships for the extreme events criterion are plotted in Figure 7-5. Here, the new ranking method performs 140% better than the AHP on the coefficient of determination. In all three cases, the difference in the value function gets larger as the criterion rating increases. That's because, for the ranking method, the criteria weights increase as the criteria rating increases and with that a larger contribution by the large-weighted criteria into the value function. Finally, although the new ranking method shows much better correlation relative to the AHP, it should be noted that the coefficient of determination are generally average. That's as should be expected since the value function depends on all four criteria and not just the criterion under investigation.

The trends are the same for the 30 bridges of chapter 7 (Inventory #2) as shown in Figures 7-6 to 7-8.

7.5. Performance of AHP on the One-Large-Criterion Scenario

If Bridge #2 (Table 7-2) takes on a rating of 93% on the bridge performance criterion while rating at 0% on the other 3 criteria, the value function (Ranking Index) for Bridge #2 would come in at exactly 93% and rank in the top 5 of the 30 bridges using the new method devised in this thesis. On the other hand, with AHP, Bridge #2 would attain a function value of 32% (AHP Prioritization Index) and its ranking would drop down to 29th position out of 30. Therefore, with AHP, Bridge #2 goes to the bottom of the 30 bridges and, consequently, does not get programmed for intervention. Now, what if the 93% rating for Bridge #2 was on the criterion of extreme events vulnerability, where such a high rating would suggest that Bridge #2 is at significant risk of failure if it encountered a climate-triggered extreme event?

More importantly, the example illustrates that the new ranking method does perform as intended: every criterion included in the formulation is important enough to single-handedly govern the decision to program Bridge #2 ahead of other bridges slated for intervention. In this case, the one criterion was bridge performance.

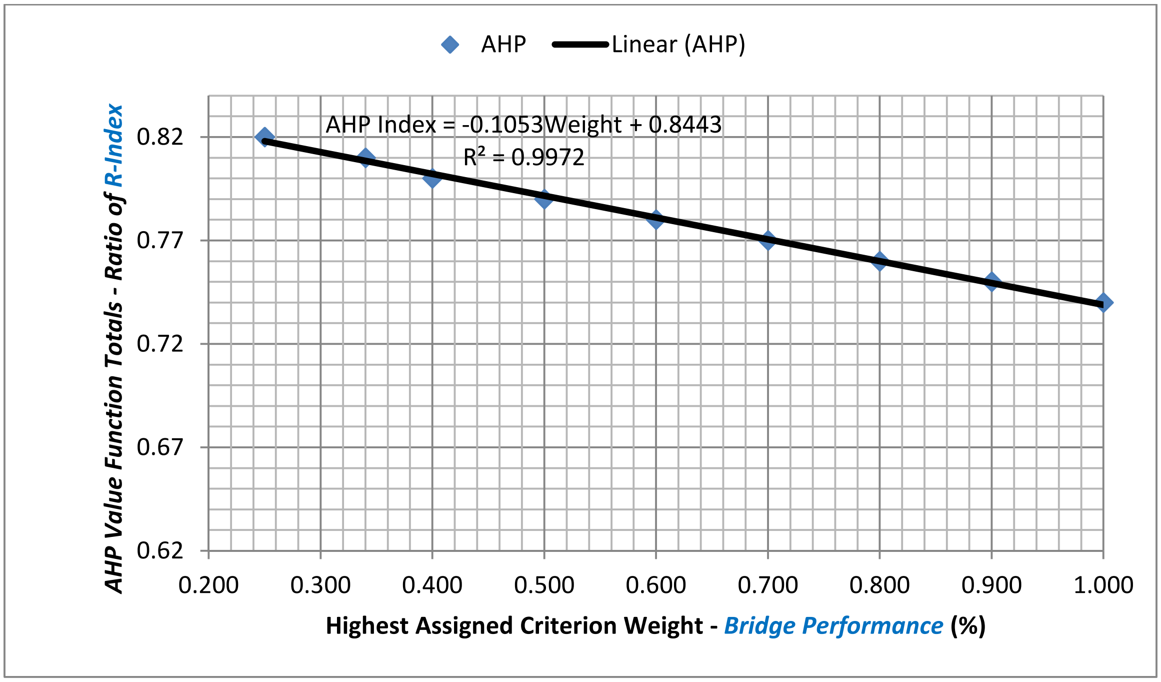

Fig. 7-1 Maximization of the Value Function: Ranking Method Vs AHP's Prioritization

Table 7-5 Maximization of the Value Function

(*Extreme Events as Largest-Weighted Criterion*)

	Performance	Utility	Extreme Events	Extreme Loads	Value Function Totals (AHP)	Ratio of R-Index Totals
1	0.25	0.25	**0.25**	0.25	1933	0.82
2	*0.162*	*0.309*	***0.334***	*0.189*	*1,959*	*0.83*
3	0.15	0.3	**0.40**	0.15	1,965	0.84
4	0.15	0.25	**0.50**	0.10	1,971	0.84
5	0.10	0.20	**0.60**	0.10	1,989	0.85
6	0.10	0.10	**0.70**	0.10	1,994	0.85
7	0.0	0.20	**0.80**	0.0	2,023	0.86
8	0.0	0.10	**0.90**	0.0	2,029	0.86
9	0.0	0.0	**1.0**	0.0	2,035	0.87

R-Index Total: 2,348

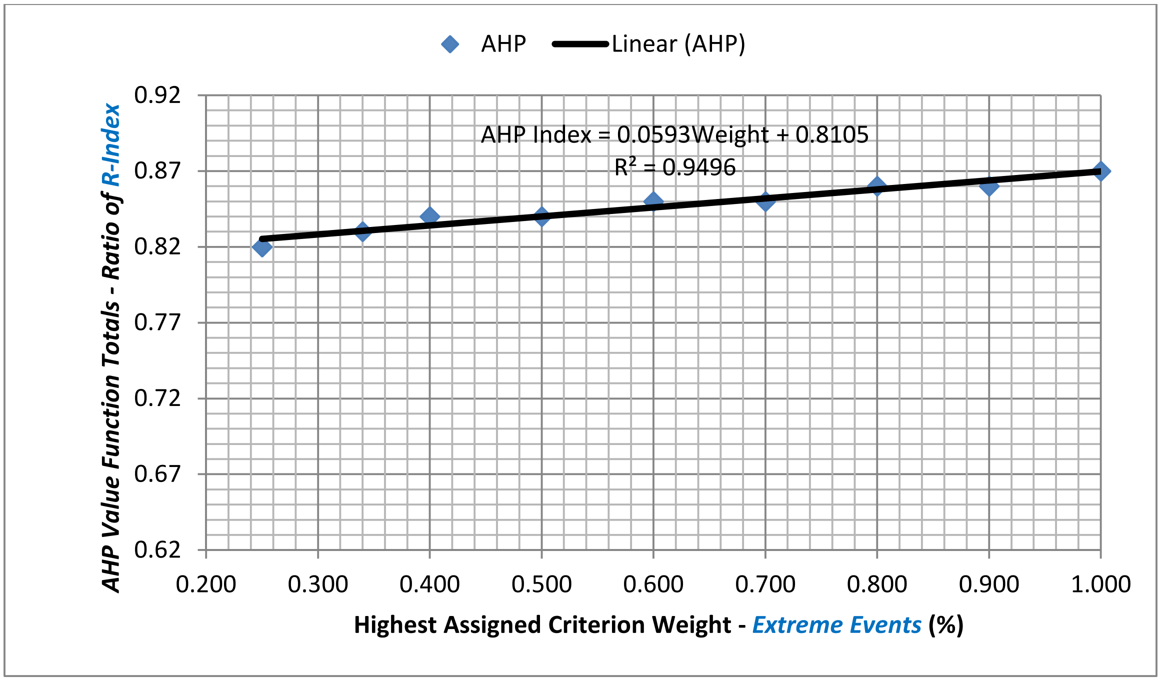

Fig. 7-2 Maximization of the Value Function: Ranking Method Vs AHP's Prioritization

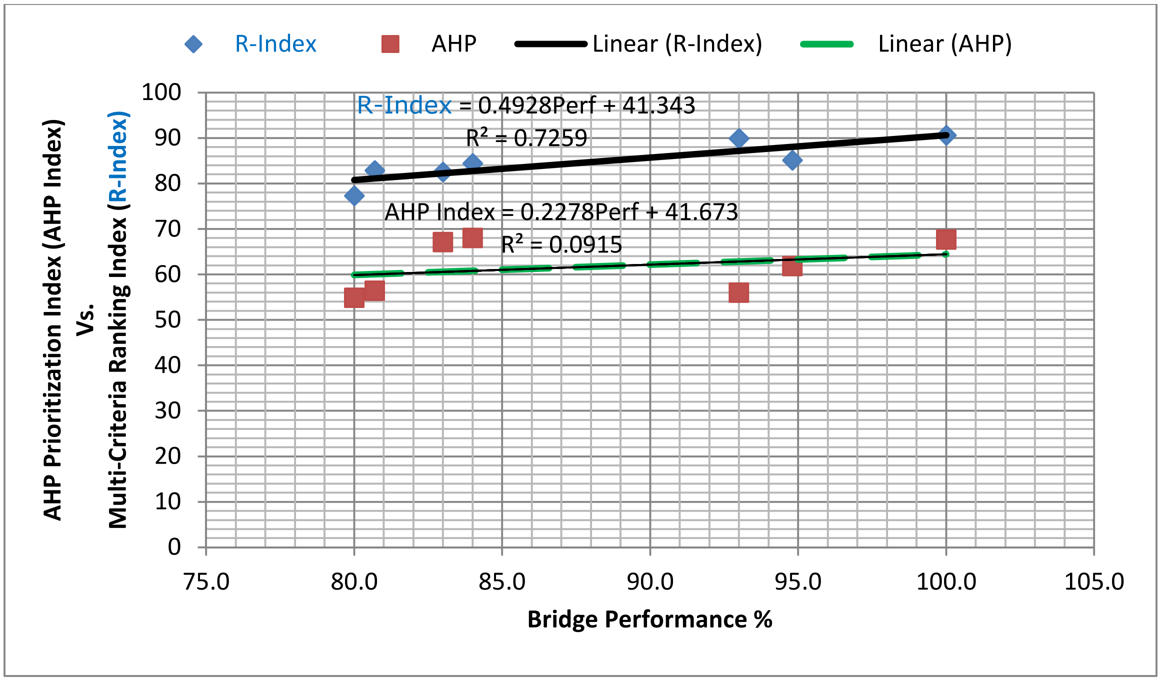

Fig. 7-3 Ranking Method Vs AHP Prioritization (Bridge Performance Criterion)

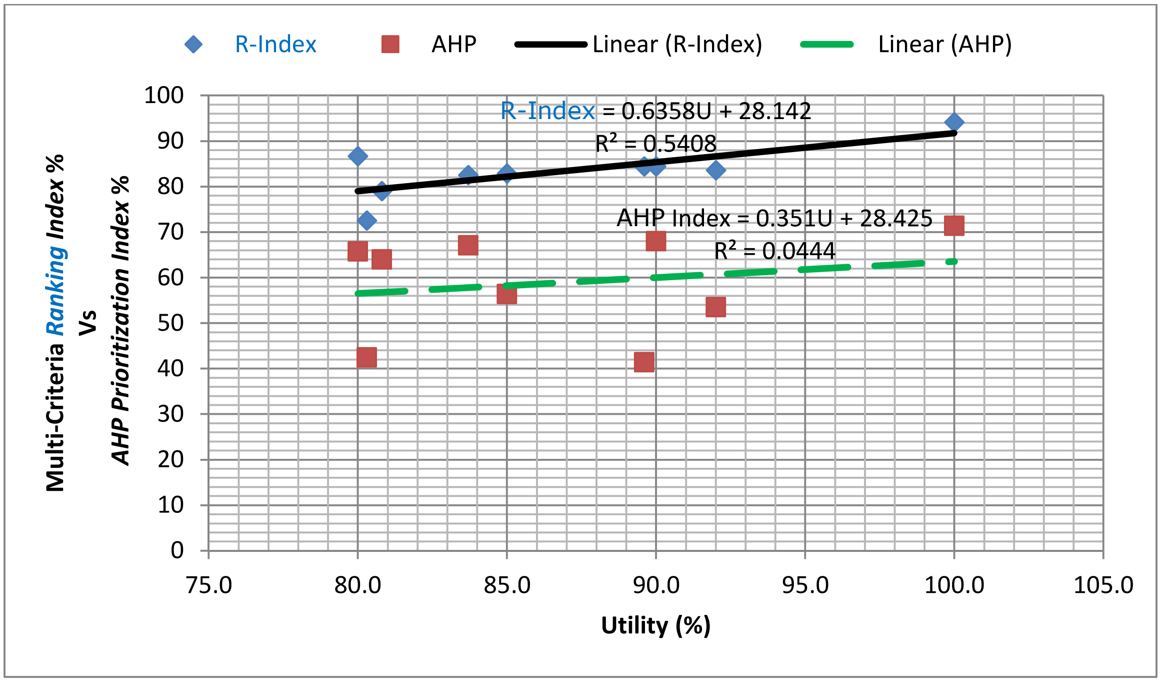

Fig. 7-4 Ranking Method Vs AHP Prioritization (Utility Criterion)

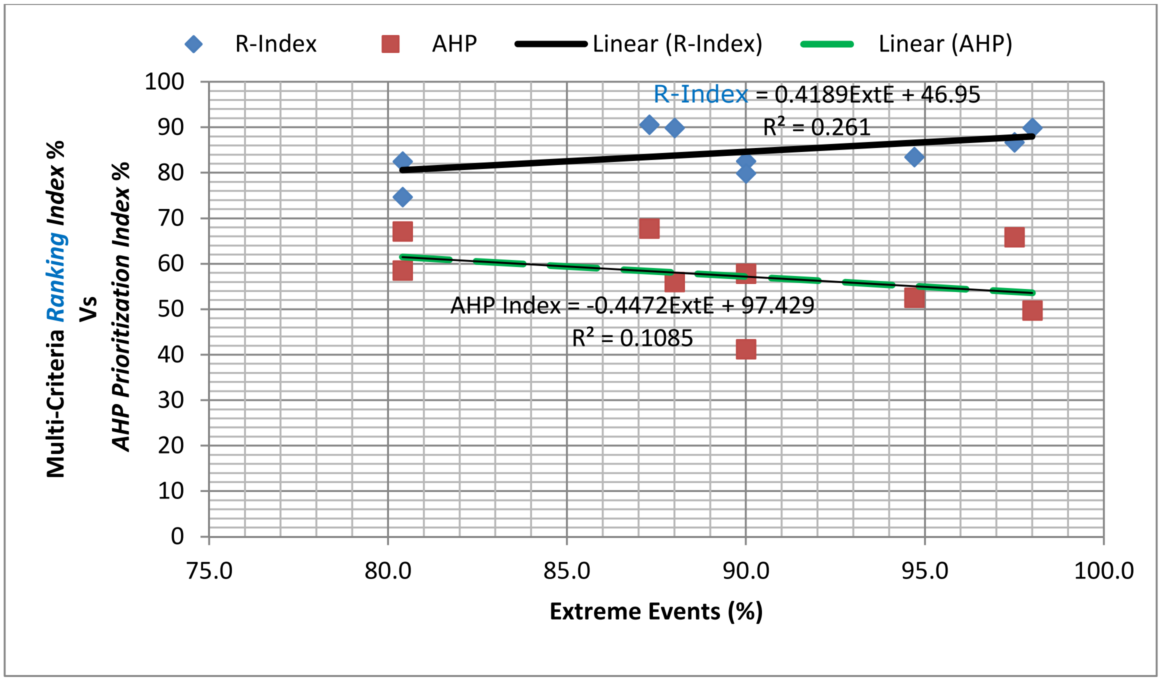

Fig. 7-5 Ranking Method Vs AHP Prioritization (Extreme Events)

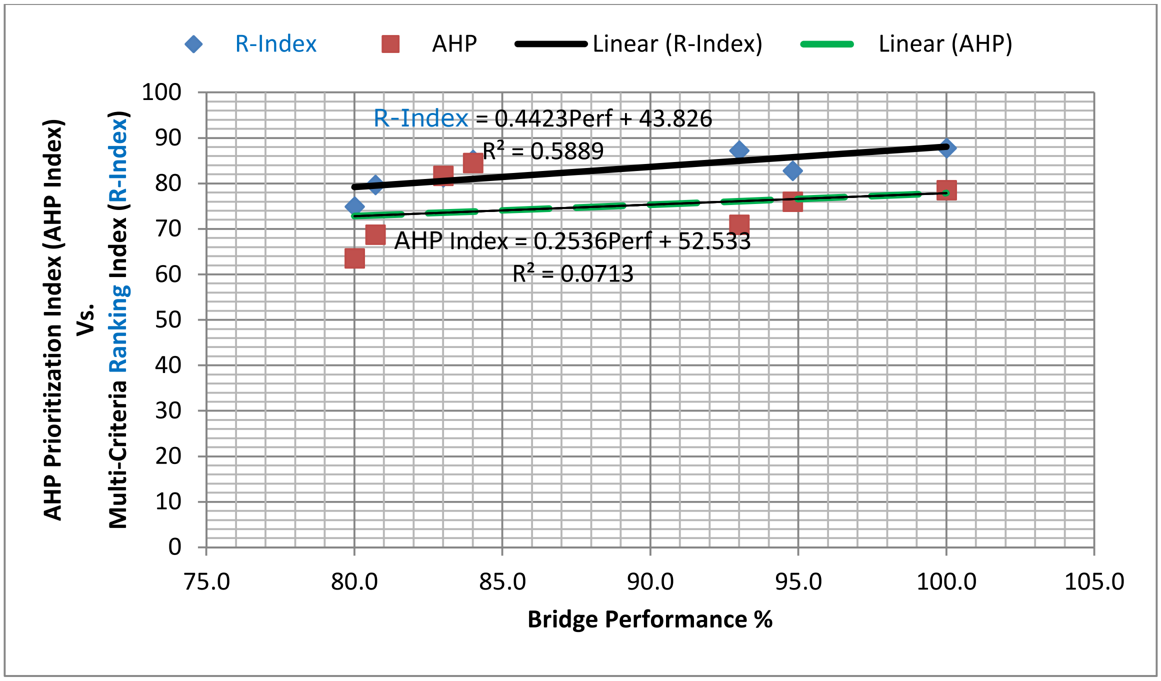

Fig. 7-6 Ranking Method Vs AHP Prioritization (*Bridge Performance*) – Inventory #2

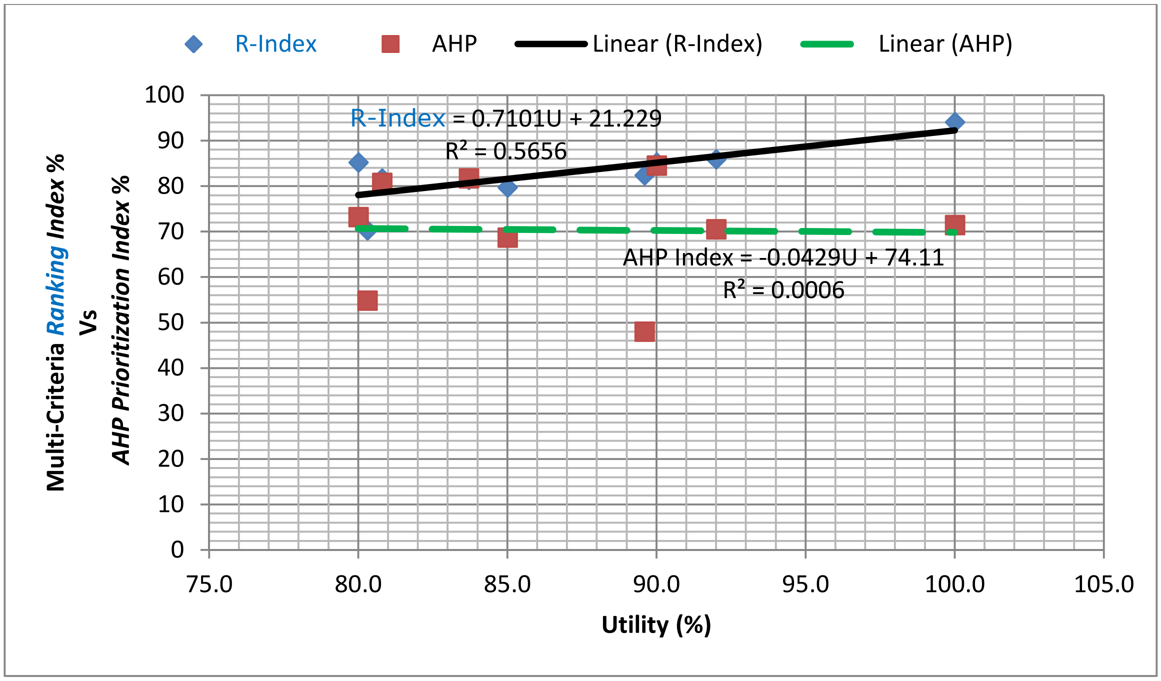

Fig. 7-7 Ranking Vs AHP Prioritization (*Utility*) – Inventory #2

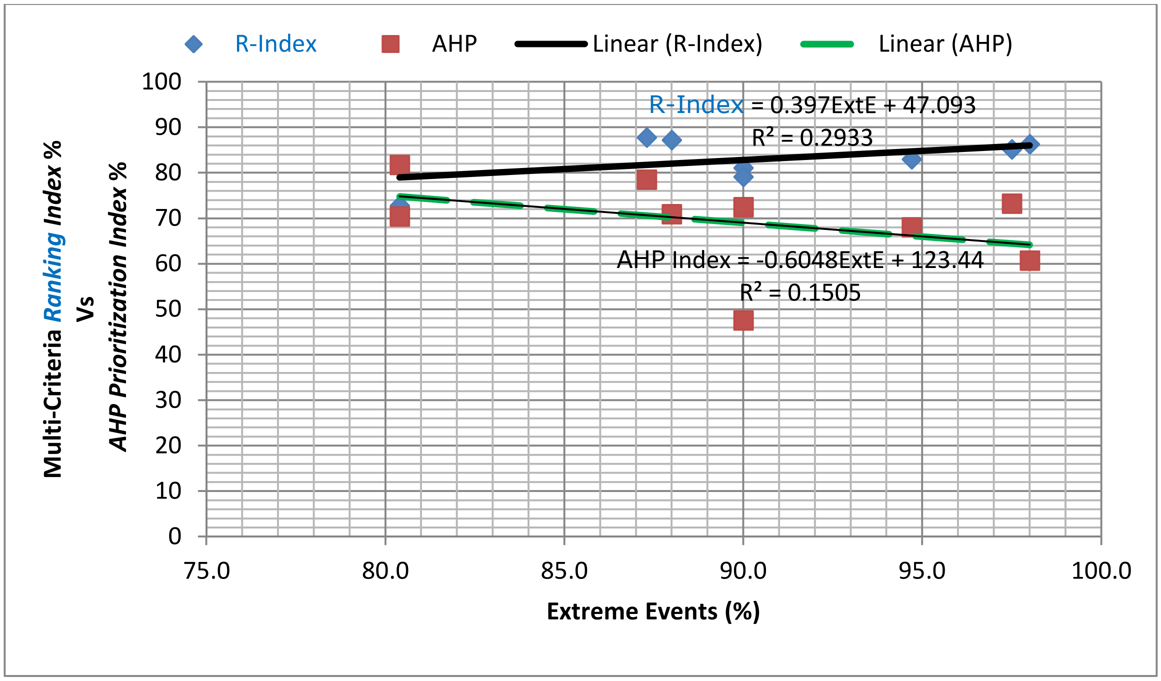

Fig. 7-8 Ranking Method Vs AHP Prioritization (*Extreme Events*) – Inventory #2

7.6. Method Verification

By testing the new method against the well-known AHP on selection efficacy, maximization of the value function, correlation between criterion rating and the *Ranking Index*, and performance on the one-high-rated-criterion scenario (Sections 7.2 to 7.5), it has been verified that the new ranking method performs as contemplated in its formulation. The performance of the Method is also compared with AASHTOWare BrM (formerly known as Pontis) of the US (in Chapter 6).

7.7. Summary

In this chapter was undertaken a comparative study of the performance of the new ranking method for the selection/programming of competing bridge projects versus the performance of the familiar Analytical Hierarchy Process (AHP). The two methods were compared on the following scores: selection efficacy, maximization of the value function, correlation between each criterion and the value function, and performance on the one high-rated criterion.

The new ranking method performed much better than the AHP as it selected for early implementation all the bridges that scored 90% or higher on *any* of the four criteria, including bridges scoring very high on potentially extremely risky situations involving climate-triggered extreme events and climate-triggered extreme loads. On maximization of the value function totals, the new method consistently scored 20% higher than the AHP across the entire spectrum of nine weight schedules. Tracking of the correlation between individual criteria rating and the resulting ranking index, on the one hand, and AHP Index, on the other hand, showed that the coefficient of determination for the former was consistently higher, in some cases up to 1,000% higher. Finally, on the one high-rated criterion, the new ranking method proved to be efficient in converting a one-criterion high rating to a high ranking index whereas the AHP consistently failed.

Chapter 8

Summary and Conclusions

8.1. Summary

This research was devoted to studying the continuous management, under budget constraint, of highway bridges while accounting for both the traditional criteria and the new criteria related to the projected impacts of climate change on transportation infrastructure in this century. In very cold regions such as the Canadian Arctic and the state of Alaska, the resilience of highway bridges to both climate-triggered extreme events and climate-triggered extreme loads are very important criteria that must be taken into consideration in deciding what projects get implemented and in what order. In particular, the research investigated a multi-criteria ranking method for determining the order of implementation of bridge projects that could result in the selection of a mix of projects that perform at the highest levels on all the criteria.

The research developed a method for the climate-triggered extreme events vulnerability rating of highway bridges, which calculates the Resilience percent of highway bridges by way of a formulation that assigns weights to Resilience Indicators (abutment washout, pier scour, abutment erosion, deck flooding, and abutment permafrost stability) against which the bridge is to be rated on corresponding capacity measures (hydraulic capacity, pier scour protection, and abutment thermal insulation or the presence of pile foundation).

Second, in what would ultimately be the question that civil engineers will be required to answer, this research proposed an approach to the calculation of the magnitude or intensity of climate-triggered extreme loading that would cause the collapse of a bridge structure in cold regions. The method suggests a new *Load Case* based on existing load cases of the Canadian Highway Bridge Design Code CAN/CSA-S6 to determine the magnitude of climate-triggered extreme failure loads such as ice-accretion and pier scour.

To account for the rating of the bridges on the two new criteria alongside the two traditional criteria of bridge performance and utility, there was need for a method that can rank competing bridge projects on four or more criteria. Whereas multi-criteria optimization of bridge projects' selection/programming is considered to be a *Non-deterministic Polynomial* hard (NP-hard) problem for which there is yet no exact solution, the present work offers a new approach to bridge projects' selection that represents an improvement on the existing state of practice. The proposed method is a direct, non-iterative, weighted-criteria ranking technique that is based on criteria *weights* derived from the bridges' rating on the various criteria, which also produces selection results that are better than the results of prioritization based on the Analytic Hierarchy Process. Further, because iteration is eliminated, the new method significantly cuts down on computer run time as compared to the best known existing method (AASHTOWare ***BrM***) offered by the Federal Highway Administration (FHWA) in the United States.

8.2. Conclusions

Taken together, the following conclusions can be drawn from the various components of the research reported in this thesis, which had the following three themes: resilience rating of highway bridges against climate-triggered extreme events, determination of the magnitude of climate-triggered extreme load that would produce bridge failure, and multi-criteria ranking of competing bridge projects in bridge management systems.

- As part of the present research, a method has been devised for extending the asset management scope for highway bridges beyond the usual bridge condition monitoring to incorporate the resilience rating of highway bridges against climate-triggered extreme events.
    - The method provides for a procedure for determining weights to be applied to each *resilience indicator* based on replacement cost, failure consequence, and user cost/inconvenience. The method also provides *Guidelines* for rating of the bridges against climate-related *capacity measures*.
    - The *Rating Guide* cited above can be incorporated as a new section in existing *Bridge Inspection Forms*, which transportation agencies and their bridge inspectors can use for rating highway bridges against climate change impacts.

  - By applying the said procedure to 14 highway bridges in the Canadian Arctic, it has been illustrated how significant public investments in infrastructure improvement could be laid waste by the failure of public transportation agencies to consider climate-triggered extreme events in the design, rehabilitation, and asset management practices for highway bridges.

- Another problem addressed in this research pertains to the structural evaluation of the magnitude of climate-triggered extreme loading that would produce structural failure of a bridge in the presence of nominal levels of live loads. This problem has been tackled by proposing a new load case in the Canadian Highway Bridge Design Code to comprise un-factored live load, un-factored dead load, and climate-triggered extreme loads. Using the proposed method, the magnitude of ice accretion that would produce failure of a truss bridge is calculated as the thickness of ice on the steel truss members that exhausts the reserve strength of the bridge. Similarly, the magnitude of pier scour that would produce failure of a multi-span bridge supported on concrete piers is calculated as the flood discharge height of water that would result in the bending failure of the pier.

- In the final component of the research, a non-iterative, one-direction method for the ranking of competing bridge projects on multiple criteria has been proposed and demonstrated for 4 criteria, namely, bridge performance, utility, vulnerability to climate-triggered extreme *events*, and vulnerability to climate-triggered extreme *loads*. Based on the review of the existing methods and the results of the present study, the following conclusions have been derived.
  - Using the new method developed within the present research, bridge projects forming a part of an inventory-wide intervention program can be rapidly ranked to reflect the costs and benefits to the transportation agency, bridge performance enhancement, the risks posed by climate-triggered extreme loads, and the risks posed by climate-triggered extreme events.
  - By using *weights* derived from the bridges' rating on the various ranking criteria, iteration is eliminated in determining the order of bridge projects implementation

using the proposed method, and the computer run time is significantly reduced as compared to that in traditional ranking methods such as the one provided in AASHTOWare ***BrM***.

- The method accounts for such intrinsic attributes of the bridge/project as the bridge rehabilitation cost, the bridge performance prior to intervention, the bridge performance following intervention, cost savings per dollar spent on the intervention (utility), bridge clearance above the 100-year flood elevation, availability and length of detour routes, etc.
- The ranking criteria to be used with this method should be limited to only those criteria that the transportation agency considers to be each important enough to govern the decision to program a bridge project ahead of other bridge projects slated for implementation. Bridge performance, utility, climate-triggered extreme loads, and climate-triggered extreme events are proposed as meeting that condition.
- The proposed method represents an improvement on existing methods, including the *Analytic Hierarchy Process AHP*. That is because, under budget constraint, the method can in one fell swoop select projects for implementation such that not only those projects that produce the highest overall inventory performance per dollar spent are programmed early, but also those projects that serve to prevent sudden bridge failure occasioned by climate-triggered extreme events/loads as well as projects that attract the highest non-performance benefits for tax payers. Further, the proposed method can rapidly rank projects for any size of inventory (such as the 50,000-bridge Texas DOT inventory) as it is a one-direction procedure requiring no iterations.

8.3. Contribution

1. Multi-Criteria optimization of bridge projects' selection is a difficult problem in Bridge Management. The best solution presently available for a maximum of 2-criteria optimization is iterative and could certainly be improved on. In contrast, the method developed in this thesis is a *ranking technique* that maximises the value function,

eliminates iteration, and is based on weights derived from the bridges' rating on the various criteria.

2. Secondly, the proposed method for resilience rating of highway bridges in cold climates represents an innovative and practical formulation for translating the impact of climate change effect into an engineering tool for the continuous management of highway bridges against climate-triggered extreme events. The formulation comprises *resilience indicators* and corresponding *capacity measures*. It is expected that the method will influence future studies of climate change resilience/vulnerability rating of transportation infrastructure.

3. Finally, a method has been devised for calculating the magnitude of climate-triggered extreme load (such as ice accretion or pier scour) that would cause the collapse of a highway bridge. Further, the proposed new Load Case provides a convenient way to estimate the potential for failure of a highway bridge when it encounters a climate-triggered extreme loading.

8.4. Limitations and Recommendations for Future Work

Limitations

- The method for climate change resilience rating of highway bridges developed in this thesis is based on climate projections for Alaska and the Canadian Arctic Region. Some adaptation may be required to make it applicable to other climatic regions.
- The method for structural capacity resilience rating of highway bridges against climate-triggered extreme pier scour loading was based on the assumption that the flexural strength design of the concrete pier was based on the braking force load case. To apply the method to a real highway bridge, the *Design Notes* for the original design should be consulted to see exactly what load cases were considered in the said original design. Further, the effect of hydrostatic forces on the downstream face of the pier should be accounted for in the analysis in order to improve the accuracy of the results.

- The results obtained with the new methods proposed in the thesis could not be compared with previous results by other researchers because no studies could be located in which actual bridge inventory data were deployed for projects' selection ranking or optimization.

Recommendations for Future Work

- The methodology proposed within this research for climate change resilience rating of highway bridges should be modified and adapted for tropical and hot climate regions.
- The weight parameters for the weighted-criteria ranking method introduced in this thesis comprised the rating of the bridge project on each criterion as well as the ranking of the bridge project on each criterion relative to the other projects. Future work should investigate what additional weight parameters might be available that measure the performance of each project on the various criteria relative to the other competing bridge projects.
- Mathematical methods for optimization in selection problems should be investigated to provide an alternative approach and to determine whether or not the method developed in this thesis does in fact maximize the *Ranking Index* (or comes close to it) in comparison to such mathematical methods.

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Appendix

Publications arising from the Thesis

Journal articles

1. Ikpong, Anthony and Bagchi, Ashutosh. 2015. *New Method for Climate Change Resilience Rating of Highway Bridges*. **ASCE Journal of Cold Regions Engineering**, 29 (3): pp.1-15

2. Ikpong, Anthony and Bagchi, Ashutosh. 2016. *Managing Highway Bridges against Climate-Triggered Extreme Loading in Cold Regions*. **ASCE Journal of Infrastructure Systems** (accepted April 2016, published online DOI: http://dx.doi.org/10.1061/(ASCE)IS.1943-555X.0000318).

3. Ikpong, Anthony, and Bagchi, Ashutosh. *A Direct Non-Iterative Method for Multi-Criteria Prioritization of Competing Bridge Projects Considering Climate-Triggered Extreme Events*, **Journal of Civil Engineering and Management** (submitted July, 2016).

4. Ikpong, Anthony, Bagchi, Ashutosh, and Chandra, Amit. *Criteria Weights for Multi-Criteria Optimization of the Selection of Competing Highway Bridge Projects*. **Journal of Multi-Criteria Decision Analysis** (submitted August, 2016).

5. Ikpong, Anthony, and Bagchi, Ashutosh. *A New Method for Determining Climate-Triggered Extreme Load Effect on Highway Bridges in Cold Climate and Associated Vulnerability*. **Journal TBD** (in preparation).

Conference articles

6. Ikpong, Anthony and Bagchi, Ashutosh. 2012. *Exploring the Concept of Bridge Functional Index in the Context of Climate Change Impacts on Transportation Infrastructure*, Canadian Society for Civil Engineering Conference, Edmonton – Alberta.

7. Ikpong, Anthony and Bagchi, Ashutosh. 2012. *21st Century Bridge Management Systems – A New Method for Ranking Competing Bridge Projects and Programs*, Canadian Society for Civil Engineering Conference, Edmonton – Alberta.

8. Ikpong, Anthony. 2013. *The Canadian Arctic Method for Rating Highway Bridges against Climate Change Impacts*, a Presentation to the Structures Standing Committee of the Transportation Association of Canada at the TAC Annual Meeting, Winnipeg – Manitoba (invited paper).

9. Ikpong, Anthony and Bagchi, Ashutosh. 2013. *Structural Analysis & Load Rating Issues in Bridge Management*, Canadian Society for Civil Engineering Annual Conference, Montreal.