Leadership in Sustainable Infrastructure

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Vancouver, Canada

May 31 – June 3, 2017/ *Mai 31 – Juin 3, 2017*

RESILIENT INFRASTRUCTURE PLANNING A RISK-BASED ANALYSIS PROCEDURE

St. Michel, Gary[1,4], Reggin, Alan[2] and Leung, Albert[3]
[1,2,3] Tetra Tech Canada Inc., Canada
[4] Gary.St.Michel@tetratech.com

Abstract: In recent years, civil infrastructure asset management has increasingly relied on risk as a basis for prioritizing capital expenditures related to existing infrastructure assets. The US Army Corp of Engineers (USACE) has developed, and now uses, a methodology whereby the Probability of Unsatisfactory Performance of an asset is predicted and the consequences of the unsatisfactory performance are quantified and monetized. The technique is published in the USACE document EC 1110-2-6062 “Risk and Reliability Engineering for Major Rehabilitation Studies”. The authors have recently combined this USACE Risk and Reliability technique with traditional Life Cycle Cost Analysis based Asset Management. In the analysis, reduction in risk associated with alternative courses of preservation activities (called strategies) for a given asset, is calculated and considered as part of the benefit of the strategy. A cost/benefit comparison between the various life cycle preservation strategies for a given asset informs the owner as to how much capital expenditure and which course of preservation activities can be justified. The technique also readily provides for cross-asset comparisons and capital allocation where an agency has a portfolio of diverse assets. That methodology was published as part of the ASCE’s Ports 2016 Conference and entitled, “A Risk-Based Structural Assessment Approach for Port Metro Vancouver’s Asset Management” (Ghalibafian, et al. 2016). Taking the process one step further, the authors’ company has developed a methodology for bringing consideration of asset resiliency to climate change into infrastructure asset management life cycle cost analysis. This paper first briefly summarizes the Risk and Reliability based life cycle cost analysis approach and then presents the technique for monetizing the climate-based risk and demonstrates how owner agencies can inform themselves regarding how much expenditure can be justified in making infrastructure more resilient to either climate change or age-related deterioration.

Keywords: Climate Change, Resilient Infrastructure, Risk-Based, Asset Management, Life-Cycle Cost Analysis.

1 INTRODUCTION

For various reasons, climate change among them, some of our existing civil infrastructure is of insufficient capacity to protect owners and users from the risks associated with an unanticipated loss of capacity. As an example, a cloud burst might overwhelm the capacity of a roadway culvert leading to a washout. The washout forces a road closure for several days until a temporary, localized detour can be installed and the roadway reopened in a limited way while a new and presumably larger capacity culvert is installed. In the meantime traffic is detoured, in some cases in Northern Canada detours can be hundreds of kilometers, while the temporary measures are implemented. The financial consequences are composed of the vehicle operating and user delay costs associated with the detour as well as the infrastructure owner’s cost to replace the washed out culvert. The consequences in some extreme cases can run into the millions of dollars.

Using a hypothetical example, this paper lays out a rational, life cycle cost and risk based methodology to first of all screen an existing portfolio of infrastructure assets to determine economically justifiable candidate projects for adding resiliency and secondly to inform owners as to an optimal level of resiliency as part of the project level resiliency upgrade designs.

2 RISK AND RELIABILITY BASED ENGINEERING FOR INFRASTRUCTURE REHABILITATION

In 2011 the US Army Corps of Engineers (USACE EC 1110-2-6062, 2011) published its guide to risk and reliability based engineering as related to civil structures. It uses a generally accepted definition of risk as the product of the probability of an event happening and the economic consequences of the event. As a structure ages, its capacity is reduced through material degradation such as corrosion, concrete disintegration and erosion of foundations while at the same time loading demand may be increasing through heavier and more frequent truck loads on a bridge for example or shorter return periods for the structures original design event. The reliability is defined as the probability of loading demand remaining less than structural capacity in a given year of a structure’s life. The USACE expresses reliability of a structure in terms of the inverse of its Probability of Unsatisfactory Performance (Pup). The Pup is typically near zero when a structure is new and approaches unity when the demand is expected to exceed capacity. Figure 1 illustrates the relationship between Pup and Reliability.

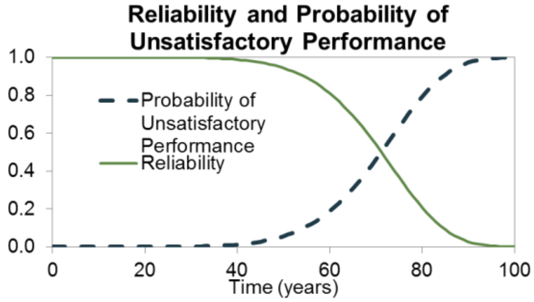

Figure 1: Reliability and Probability of Unsatisfactory Performance

The probabilities are determined through approved methods, such as Monte Carlo simulations using statistical distributions of the capacity/demand ratio’s calculation input parameters such as steel and concrete sections, rate of scour and event return period as predicted from using various materials degradation and event return period models.

Of further interest, the USACE methodology applies the concept of monetizing the consequences of unsatisfactory performance placing a financial value to the economy for such things as loss of use, environmental damage, loss of recreational benefits and where applicable as in the case of large dams, loss of life. The risk expressed in the cost of the consequences ($Consequences) multiplied by Pup quantifies the risk ($Risk) in a given year. If the $Risk is greater than the financial cost of the rehabilitation project it can be financially justified. Quantifying monetarily the $Risk of the unsatisfactory performance of civil infrastructure can be readily applied to managing a portfolio of Infrastructure Assets but also as the basis for defining robustness for new infrastructure design. The technique has been applied in the arena or Public Private Partnership (P3) projects where the consequences of unsatisfactory performance are given by the infrastructure owner in terms of non-compliant performance penalties.

3 RISK-BASED LIFE CYCLE COST ANALYSIS PROCEDURE

Life Cycle Cost (LCC) of an asset has historically included direct ownership costs such as Capital, Rehabilitation, Maintenance & Operations and Disposal or Salvage costs. More recently the set of costs to be considered has grown to include user costs and environmental costs (St. Michel et al. 2011). Now, with a monetized value for risk, $Risk can be included in the LCC. Figure 2 compares the increase in $Risk over time, due to deterioration of the asset, with and without advanced preventative maintenance. When $Risk is considered as part of the LCC, the Present Value Cost (PVC) of the advanced maintenance can be directly compared to the PVC of the annual value of $Risk.

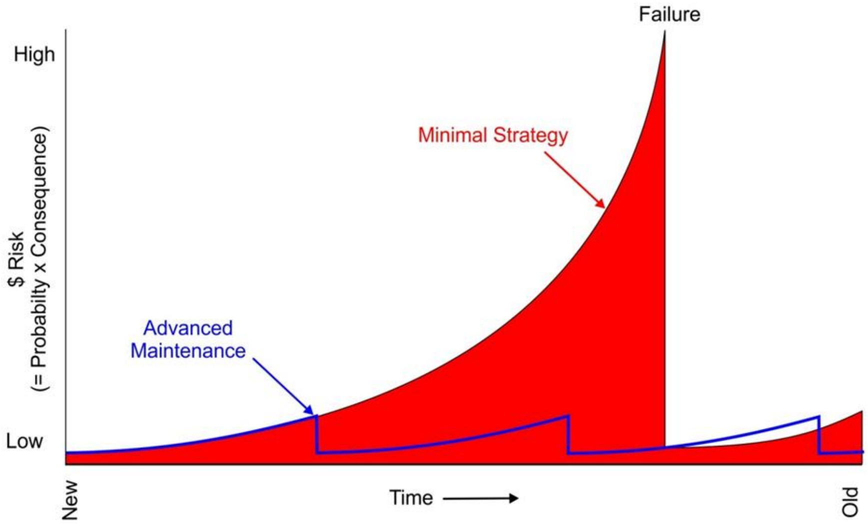

Figure 2: $Risk versus Time

A Life-Cycle Cost Analysis compares the LCC of two or more alternative solutions for providing the infrastructure asset. These alternatives solutions are here-in referred to as Strategies. The LCCA is intended to inform the analyst as to which Strategy has the lowest LCC. However it is not possible to accurately compare total LCC without considering the risk associated with each. The addition of $Risk to the LCCA resolves this problem. The difference in Strategies may be fundamental, a concrete structure versus a steel structure for example, or very subtle such as variations in maintenance and rehabilitation regimes for identical original structures. The combinations and permutations of differing original structures and differing maintenance and rehabilitation regimes can quickly multiply. The lowest possible LCC cannot be determined unless all possible feasible Strategies have been considered. It is not possible to imagine all possible Strategies, however considering more strategies leads to a lower LCC solution (Palsat, et al. 2016). The concept of considering multiple strategies as part of an LCCA is here-in called a Multi-Strategy LCCA. The concept is illustrated in Figure 3.

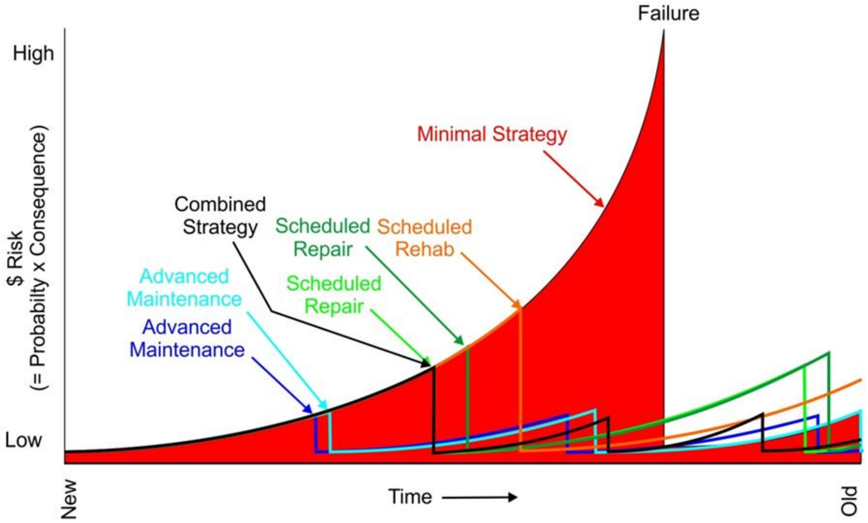

Figure 3: Multi-Strategy LCCA

A Multi-Strategy LCCA which includes $Risk is called a Risk-based Analysis Procedure (RAP) is particularly useful for determining the design criteria of assets. It can economically justify the robustness of a structural section based on the reduction of the $Risk of deterioration and can economically justify the capacity of a structure based on the return period of a design event such as a flood.

4 QUANTIFYING $RISK IN TERMS OF USER COSTS AND OWNER COSTS

The concept of applying the Multi-Strategy LCCA to developing design criteria is illustrated using a hypothetical example of a roadway culvert draining a 0.65 Square Kilometre basin in northern Canada. The roadway carries an Annual Average Daily Traffic of 465 vehicles of which 20% is commercial (truck) traffic. The volume of traffic is rising at 1% per year. The user consequences of a washout of this culvert is considered to be road closure and a 462.5 km detour during the 15 day culvert replacement and embankment reconstruction period. The consequences to the owner are considered to be the culvert replacement and roadway reconstruction costs. The culvert was installed 25 years ago and sized to meet the requirements of a fifty year return period, short-duration rainfall event. Due to changes in climate, the same rainfall event currently has a 30 year return period. The culvert age and climate effects combine so that the owner agency currently has a greater risk of deterioration related performance problems because the pipe is 25 years old as well as the greater risk of exceeding the design capacity. The owner agency is contemplating a risk reduction Strategy consisting of replacing the existing culvert with a bigger one.

Table 1 gives the infrastructure replacement costs associated with larger capacity pipes and associated roadway improvements.

Table 1: Infrastructure Replacement Costs versus Design Rainfall Return Event

Return Period	Initial Cost	Present Value Cost Replacement in 60 Years[1]	Present Value Cost for 100 Year Analysis Period
50	$ 621,000	$ 63,000	$ 684,000
100	$ 689,000	$ 70,000	$ 759,000
200	$ 757,000	$ 77,000	$ 834,000
500	$ 847,000	$ 86,000	$ 933,000
1000	$ 915,000	$ 93,000	$ 1,008,000

The direct consequences to the owner agency related to the washout of the culvert are at a minimum the replacement of the infrastructure and its associated LCC over the analysis period assumed for this example to be 100 years which would include a future culvert replacement in the 60th year of the life cycle. The value of the loss of remaining life of the washed out existing culvert is ignored when calculating $Risk in this example for simplification. The minimum consequences to the owner agency in this example is therefore taken to be $684,000, the LCC to replace the infrastructure to today's 50 year rainfall event.

The consequences to the users are computed using a combined vehicle operating and user delay cost of $0.75/km for passenger vehicles and $2.00/km for commercial vehicles traveling the 462.5 km detour for a period of 15 days yielding a user consequence of $3,225,000 in the event that the culvert is washed out in a given year.

The combined user and owner consequences of unsatisfactory performance are therefore $3,937,000. With a 30 year return period there is a 3.33% probability of the culvert failing and therefore a $Risk in year one of the analysis period of 0.0333 x $3,937,000 or $130,000. Although there is an equal chance (3.33%) of failure in each year of the analysis period, the annual probability of failure decreases over a 30 year period because the asset can only fail in a given year within the 30 year period if it has already survived the preceding years. At the start of the 30th year, although there is a 3.33% probability of failure in the 30th year, there is now only a 1.2% chance of it failing within this 30 year period because it has already survived

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[1] PVC of Infrastructure assets calculated using a 4% discount rate.

through 29 years. This deceasing probability is termed the Annual Probability of a Design Event in Figure 4. This means that there is a 64% chance that the asset will fail in the first 30 years due to a rainfall event. There is also the increasing possibility that the asset fails due to material degradation as it ages as discussed in section 2. The probability the overall Pup is obtained by combining the two Pups as shown in Figure 4.

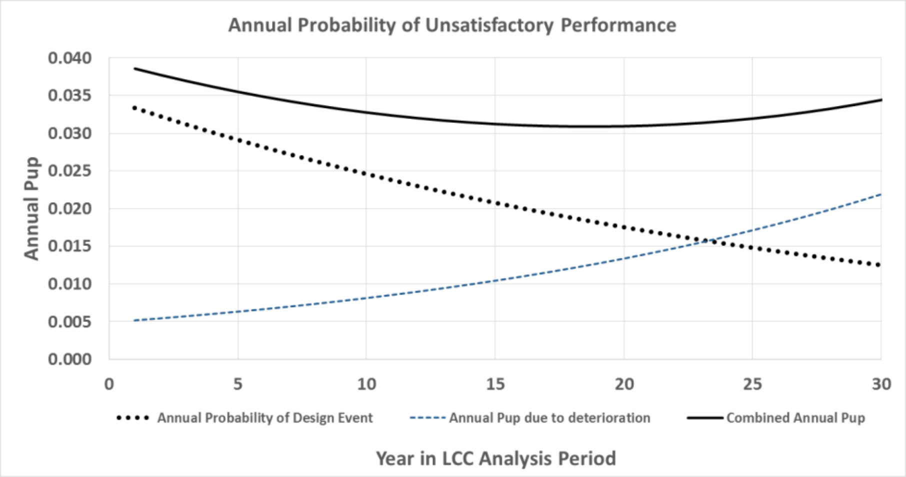

Figure 4: Total Annual Probability of Unsatisfactory Performance (30 year return period)

A culvert designed to the current 30 year rainfall return period and replaced in kind, would be expected to fail two or three times in a 100 year analysis period resulting in a PVC of $Risk of over $2 million[2] easily justifying making the existing asset more resilient to the climate change which has already occurred. This is true even taking into account the value of the loss of remaining service life of the existing 25 year old asset should it be immediately replaced.

In the absence of any further future climate change, (one possible although highly unlikely possibility), the owner agency would be faced with a decision as to how much added capacity could be justified and in what manner to increase the capacity, an armoured temporary ford, additional pipes, armoured header and wing walls, and how much structural design life should be provided initially and options for increase capacity and structure in future. The multi-strategy LCCA incorporating $Risk is a defensible mechanism for making these investment decisions.

To illustrate the usefulness of this type of analysis, the $Risk values, for this hypothetical example, for a number of different event return periods ranging from 10 years to 1,000 years have been calculated. The resultant Present Values of the $Risk for each return period can be plotted against return period and used to provide a direct comparison between PVC $Risk, infrastructure costs and event return period as shown in Figure 5.

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[2] PVC of $Risk calculated using a 4% discount rate

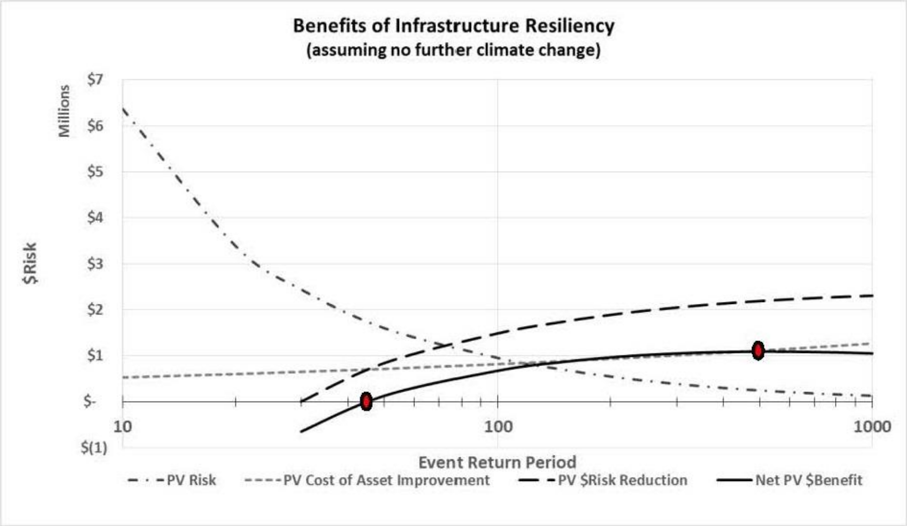

Figure 5: PV Asset Strategy Costs Compared to PV $Risk at Different Return Periods

In this example the cost of making the infrastructure more resilient is equal to the savings in $Risk at a return period of 45 Years. However the Net Benefits of a Stategy continue to rise until an event return period of 500 years is used. That is, the savings in $Risk less the cost of the added resiliency peak for today's 500 year return period. The choice to make investment decisions regarding adding infrastructure resilience prior to an event actually taking place is termed Resilient Infrastructure Planning (RIP). RIP using the Risk-based Analysis Procedure is termed RIP-RAP.

5 RESILIENT INFRASTRUCTURE PLANNING FOR CLIMATE CHANGE

It is now generally agreed that the climate is continuing to change resulting in more intense weather events in many parts of the planet, whether it be stronger wind storms, more intense rainfalls and/or snowfalls, longer droughts, and higher temperature, etc. In order to take this change into account in RIP-RAP, the Authors choose to quantify the climate change in terms of decreasing return periods, which means more frequent occurrence of a particular weather event, over the life cycle time period considered in the RAP. Different aspects of weather could experience different degrees of change in occurrence frequency; the one aspect that is applicable to a culvert design, which is the focus of this paper, would be the volume of runoff, which are controlled partly by the rainfall volume and by air temperature. To facilitate a simpler illustration of the method in determining the projected change in return period for a particular weather event, the meteorological parameter chosen for discussion in the remaining parts of this section is air temperature only. However, the same mathematical procedure would apply to the rainfall volume.

Air temperature is predicted to rise on a global scale; however the rate at which the air temperature rises varies from location to location, In general, the rise in temperature increases with latitude with greater increase near the polar regions and smaller increase near the equator. Figure 6 shows the modelled temperature increase in the 21st century published in the 2007 Fourth Assessment Report (AR4) by the Intergovernmental Panel on Climate Change (IPCC). Note that B1, A1B and A2 are three different climate change scenarios associated with various human, economic and social development in the future.

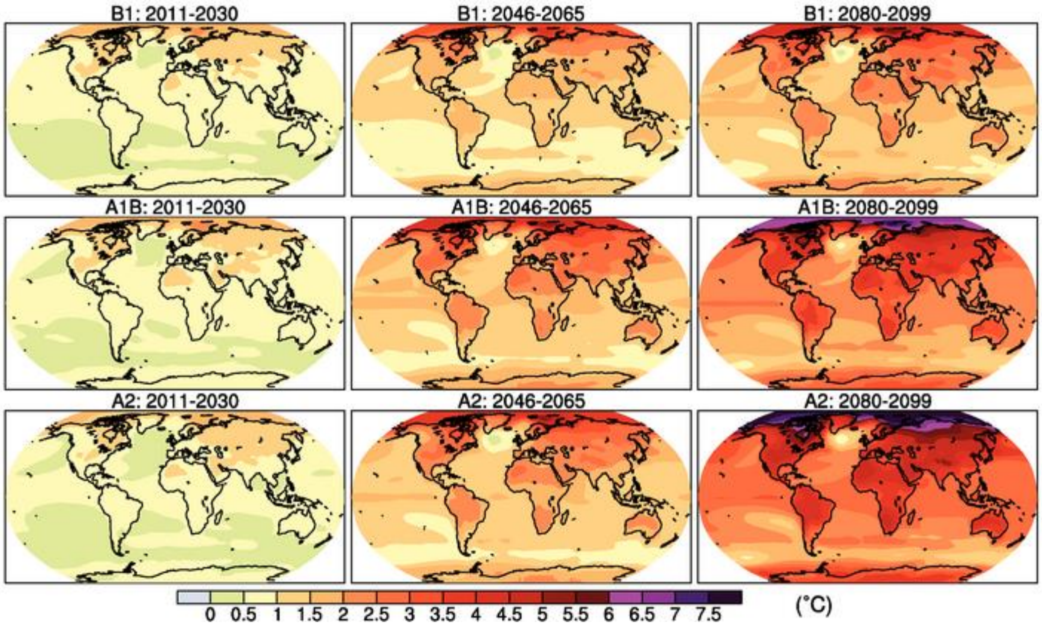

Figure 6: Predicted Rise in Temperature in the 21st Century (IPCC's Fourth Assessment Report, 2007)

The air temperature prediction shown above essentially indicates a higher probability of occurrence of warmer temperature, compared to the probability associated with air temperature in the current timeframe. To represent numerically the likelihood of a specific air temperature rise, the probability density function (PDF) were derived. Figure 7 below is a PDF plot, published in AR4 by the IPCC, for rise in air temperature for the three climate change scenarios (B1, A1B and A2) in two different time frames. The different coloured curves in the figure represent the results derived from different global circulation models that were used to predict future change in global climate.

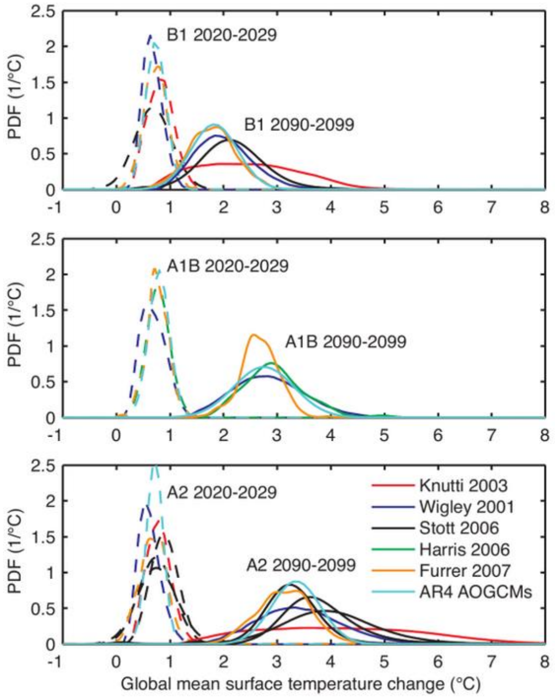

Figure 7 – Probability Density Function for Increase in Air Temperature (IPCC's Fourth Assessment Report, 2007)

Integrating the PDF numerically with respect to air temperature will produce a cumulative probability (CP) curve similar to those shown in Figure 8 below, which illustrates the CP for the three different climate change scenarios (represented by the three coloured lines).

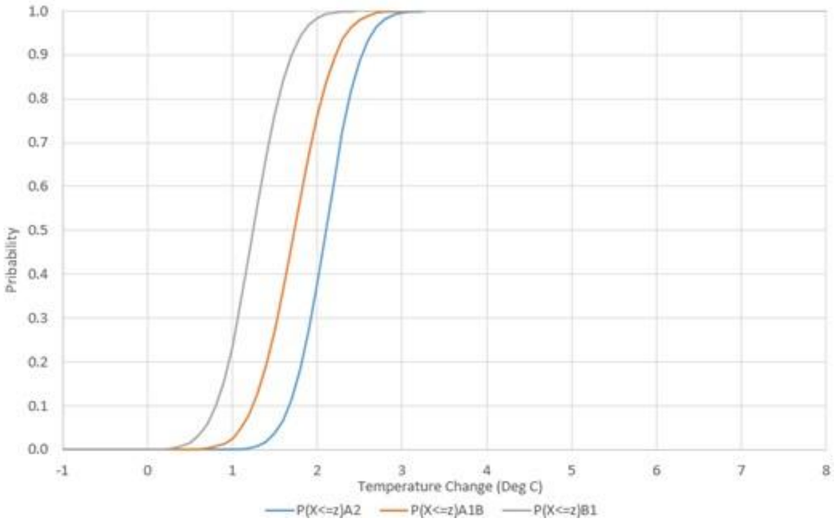

Figure 8 – Sample Cumulative Probability for Projection of Rise in Air Temperature

The CP curves tell the analyst that, in a particular year, there is, for example, a 10% probability (equivalent to 1-in-10-year return period) of experiencing an average increase in air temperature of 2.2 degrees Celsius or more). The CP curves associated with more distant timeframes would shift to higher temperatures, meaning the probability of occurrence of a chosen event, say an average air temperature increase of 2.2 degree Celsius or more, will be higher and has a lower return period. By comparing the CP curves associated with different timeframes, one can determine the change in probability of occurrence and therefore change in the risk associated with a particular weather parameter of interest.

6 INCORPORATING CLIMATE CHANGE CONSIDERATIONS IN RIP-RAP

Continuing to reference the hypothetical example defined in Section 4 the culvert has a Pup of 3.33% in the first year due to the 30 year event return period probability. The next year, year two of the analysis period, the event related probability would increase. This is modeled by gradually increasing the annual Pup of an event return period by a factor related to the rate of change in return period. In this example the return period is predicted to be halved within 50 years. That is a 30 year return period becomes a 15 year return period gradually over the next fifty years an increase in Pup of 2.5%/return period/year. The event related Pup in year 1 of the LCCA is 0.0333, the Pup in year 2 would be 0.0333 + 0.025/30 = 0.03417 and increasing linearly. The probability of the 30 year event happening in the first thirty years rises from 64% with no further climate change, to 75% when future climate change is also considered. Figure 9 represents graphically, the increase in Pup over thirty years when climate change is considered compared to the annual Pups ignoring climate change.

It must be emphasized that the choice of rate of change of event caused Pup due to an event’s return period is not the subject of this discussion. The selection of an appropriate rate of change should be made in consultation with climatologists, climate change modellers or other experts in those fields. Although the appropriate rate of change may not be linear, complex Pup models are easily dealt with using current computational tools. One might for instance presume that the increasing Pup model represents a mean rate of change with Monte Carlo simulation based reliabilities attached to the rates of change selected.

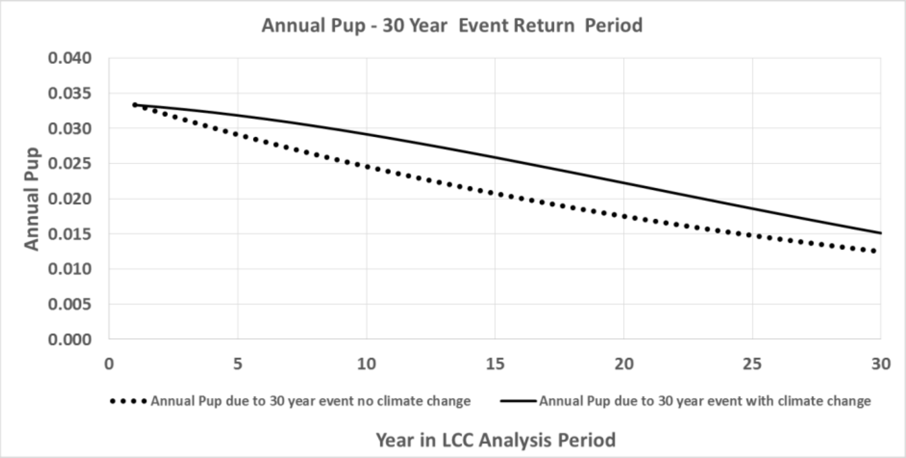

Figure 9: Annual Probability of Unsatisfactory Performance with and without Climate Change

In any case, once the climate related rate of change in Pup has been selected, the same RAP described in Section 4 can now be readily applied to any climate change caused event return period. In the example case all return periods are gradually being halved over each successive fifty year period. Over the course of a 100 year analysis period the 30 year return period would be reduced to less than a ten year event return period, a 100 year return period would be reduced to a 25 year return period. The results of the RAP applied over a range of climate change induced return period changes is given in Figure 10. The return periods modelled in this example refer to today's return period. In other words a 100 year return period would have a probability of 1% today, but a probability of 2% in year 50 of the analysis and 4% in the 100th analysis year.

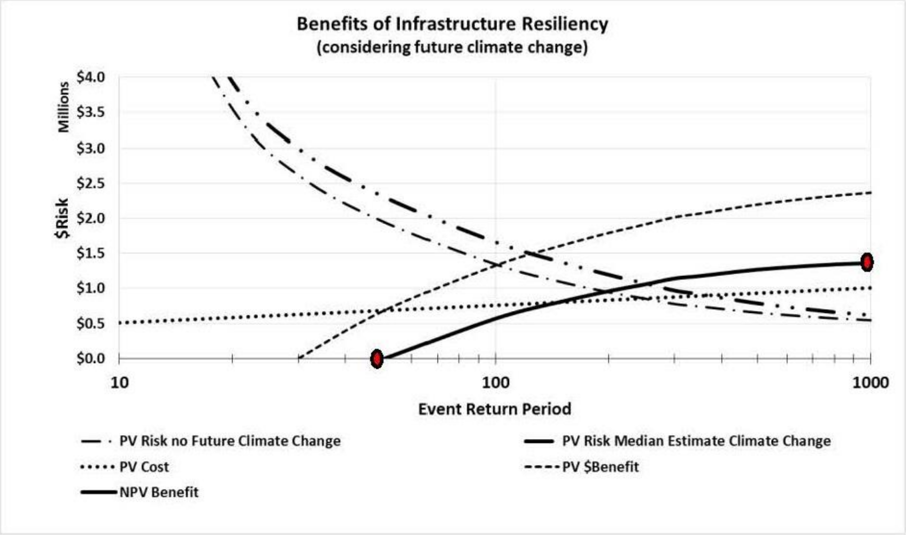

Figure 10: RIP-RAP Considering Future Climate Change

When future climate change is considered, the PVC of adding resiliency equals the PV $Risk at a 50 year event return period the PV of the Net Benefits (Reduction in $Risk – PVC of added resiliency) continue to increase to what would be today's 1000 year return period. Examining Figure 10 informs the asset owner that the existing pipe at its current 30 year design event is carrying a PV $Risk of $3,000,000 when considering both previous and future additional climate change. The design event for this asset should be in the order of a 1,000 year return period, not 50 years as was used for the original existing pipe. With expected climate change, designing for today's 50 year return period carries a PV $Risk of almost

$2,500,000 and a cost of $684,000 (from Table 1) while designing for today's 1000 year event carries a PV $Risk of just over $500,000 for a PV cost of $1,008,000.

When climate change is considered, RIP using RAP informs the asset manager that an additional $324,000 in PV cost ($1,008,000 - $684,000) of investment in added infrastructure resilience today can be justified by reducing $Risk by $2,500,000. This is a PV benefit/cost ratio of almost 6:1.

7 CONCLUSIONS

The subject of this discussion relates to a computational methodology for conducting multi-strategy life cycle cost analysis which include the monetized value of risk including those associated with climate change. Although an example showing one approach to quantifying the rate of change of the return periods of high intensity weather related events is given, it is not intended to imply that the method shown is appropriate for all types of analysis.

RIP-RAP provides a rational and economically defensible procedure for justifying investment in making existing transportation related assets more resilient as well as a basis for setting design criteria for new infrastructure and rehabilitation of existing infrastructure assets.

Because it is based on monetized $Risk it can be applied across asset classes making funding comparisons between structure, roadway, municipal, port, airport and rail improvements possible. It is therefore particularly useful where an agency controls several of these assets such a provincial/territorial governments and other large agencies such as railway companies. In particular it would have broad application in Canada's north undergoing permafrost melt and where long road/rail detours are required

Because this approach is based on return periods, it might also be appropriately applied to geo-hazard, avalanche and seismic risks.

The RAP procedure is readily programmable into Infrastructure Management System Software as has been done for the Port of Vancouver (Ghalibafian, et al. 2016) and for the Alaska Highway corridor for Public Works and Government Services Canada (Ruck, et al. 2014) making rapid and cost effective network level screening for risky assets and therefore for funding justification.

The procedure is also useful for owners developing design criteria for the redevelopment of design standards in the face of changing climate.

Moving forward it is believed that RAP with Multi-Strategy LCCA will form the bases for managing portfolios of assets to optimize the overall benefit that can be achieved with limited infrastructure funding.

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