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16. ABSTRACT

Caltrans seeks to establish a comprehensive risk scoring methodology in order to rank all statewide assets and asset vulnerabilities using a normalized risk score. This project documents an approach for calculating a risk score that incorporates bridge seismic hazards, bridge scour, landslide and rockfall hazards, and climate change vulnerability. The final report provides a summary of literature and best practices in risk management and provides a review of existing Caltrans data on seismic risk, scour, landslide vulnerability, and climate change vulnerability. The documentation on the approach for calculating the risk score is supplemented with an analytical spreadsheet that demonstrates how the methodology works. The spreadsheet allows users to input project information and change parameters to obtain the risk score. The research also identifies areas for further refinement of the approach, including key parameters that may merit further analysis to better quantify.

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Statewide Risk Scale Across Multiple Assets/Vulnerabilities
Final Report

Statewide Risk Assessment Scale

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1. Introduction

Project Purpose and Outcomes

The California Department of Transportation (Caltrans) is working to optimize strategies and programs for preserving and improving its transportation network. As part of its business strategy to enhance transportation asset management (TAM), Caltrans seeks to establish a comprehensive risk scoring methodology in order to rank all statewide assets and asset vulnerabilities using a normalized risk score.

Caltrans uses different maintenance, rehabilitation, and replacement strategies for its assets as part of the TAM program. There are different ways to assess the condition and vulnerability of the assets and prioritize the maintenance, rehabilitation, and replacement work on these assets. However, Caltrans does not have a methodology to prioritize all risks across various assets and asset vulnerabilities. An approach to normalize different scores across different assets and asset vulnerabilities allows them to be combined into a single risk scaling matrix and compared and prioritized across the State Highway System (SHS). Ultimately, this uniform approach to scoring and prioritizing risks will help Caltrans achieve a risk-based, performance driven asset management plan.

This report describes a research effort undertaken to develop a statewide risk score. The project included the following steps:

- Review a subset of vulnerabilities to the State Highway System that are currently considered in Caltrans practices. These are: Bridge Seismic Hazards, Bridge Scour, Landslide and Rockfall Hazards, and Climate Change Vulnerability.
- Develop a statewide risk assessment scale for this subset of vulnerabilities so that Caltrans can compare and prioritize them in a single scaling system. The scaling system shall include likelihood of occurrence, impact on the asset, and impact on the transportation system.
- Demonstrate how the proposed methodology works through an Excel spreadsheet analytical tool.
- Document how the framework and methodology can be applied to any risk and vulnerability. Document challenges associated with bringing these risks together for Asset Management.

- Identify any limitations in existing vulnerability information and data provided by Caltrans for this study.

Background

Managing risk is a fundamental part of TAM. All asset owners must contend with risk as they determine how best to manage their assets on a day-to-day basis, and what actions to take to maximize asset performance and minimize lifecycle costs. Key pieces of information an asset owner may wish to have are inherently uncertain, such as what asset conditions will be in the future, how effective a particular treatment might be in improving an asset, and what resources will be available for TAM. Also, the asset owner must prepare for and respond to a number of uncertain events and conditions, such as flooding, fires, and vehicle hits that may cause injuries and damage infrastructure.

Looking forward, it is likely that the uncertainty we face about the future events will grow only greater. As the transportation system continues to age, it will become more challenging to project future conditions. Further, as numerous studies describe, including the U.S. Federal Government's 2018 National Climate Change Assessment, geophysical events have become more frequent and severe in the U.S., and further increases in event frequency and severity are forecasted. This increase results from a number of factors, including but not limited to warming temperatures and increased development in coastal and low-lying areas.

A number of state DOTs and other agencies have used risk management concepts to help support their asset management decision-making. To develop its 2018 Transportation Asset Management Plan (TAMP), Caltrans prepared a TAM risk register, using as a starting point a broad-based risk register developed through the Caltrans Enterprise Risk Management (ERM) program. The register identifies risks to transportation assets, estimates the likelihood and consequences of each risk, and lists potential mitigation approaches.

Also, Caltrans has performed extensive work to evaluate specific types of risks. For instance, Caltrans was an early leader in assessing seismic risks to bridges. Caltrans initiated its Seismic Safety Retrofit Program in the wake of bridge failures experienced in the 1989 Loma Prieta Earthquake. Through this program Caltrans prioritized the retrofit needs for all of its bridges using a multi-attribute procedure that calculates a score for each bridge considering earthquake likelihood, vulnerability of each bridge to collapse, and detour distance in the event of a collapse. More recently, all of the 12 Caltrans districts have conducted climate change vulnerability assessments identifying a range of risks resulting from sea level rise and other impacts of climate change.

While Caltrans has made much progress in assessing the risks to its assets, further work remains to determine how best to prioritize risk mitigation investments. This is a complicated challenge given the multitude of different assets the agency manages and risks it faces. To help prioritize risk mitigation investments Caltrans undertook the effort described in this report to develop a statewide risk scale that can be used for prioritizing across multiple assets and vulnerabilities.

Report Organization

The remaining sections of this report are organized as follows:

- **Section 2** provides a summary of a review of the literature and best practices in risk management, focusing on the application of risk management to prioritize TAM investments;
- **Section 3** summarizes a review of sample data provided for two Caltrans districts: Districts 1 and 4. The materials reviewed include data on seismic risk, scour, and landslide vulnerability, as well as the climate change vulnerability assessments performed for each district;
- **Section 4** present a proposed risk scale;
- **Section 5** presents a set of example calculations of the risk score using the proposed scale;
- **Section 6** discusses issues related to implementation of the risk scale. It describes potential applications of the risk scale, and approach to defining probability and consequence thresholds, the data requirements for calculating the risk score, and opportunities for further improvement.
- **Appendix A** details the calculation of the risk score for locations in Districts 1 and 4. The calculation was performed using a mix of actual and representative data provided by Caltrans.
- **Appendix B** presents a peer review of the draft risk scale performed by Mr. Gordon Proctor at the request of the project team. Note the risk score calculation approach and materials in Section 6 were revised based on this review.

2. Review of Risk Management Literature and Best Practices

Risk management is a mature discipline with a long history. At the same time, risk management is a rapidly evolving field, and to date there are limited examples of transportation agencies using risk management concepts quantitatively to make investment decisions for multiple asset classes considering multiple vulnerabilities, as envisioned in the current effort. The following paragraphs describe the origins of risk management, use of risk management approaches by transportation agencies, application to TAM, and a summary of relevant best practices.

Risk Management Origins

Bernstein describes the origins of risk management in *Against the Gods: The Remarkable Story of Risk Management* (*1*). He details that examples of the recognition of risk and related concepts (i.e., in gambling) date back to ancient times. However, quantitative approaches for assessing risk were not developed until the 1600's with the development of probability theory by the French mathematicians Blaise Pascal and Pierre Fermat. Their efforts, in turn extended by others, facilitated the development of quantitative approaches for assessing risk in insurance, finance, and other areas.

More recently, significant further advances in risk management resulted from research in the 20th century in areas such as economics, game theory, and prospect theory. Bernstein describes that this research has resulted in refined risk management approaches that better account for the inherent uncertainty of future events, introduce the concept of utility in decision-making, and reflect how humans actually evaluate risk in their decisions.

Risk Management for Transportation Agencies

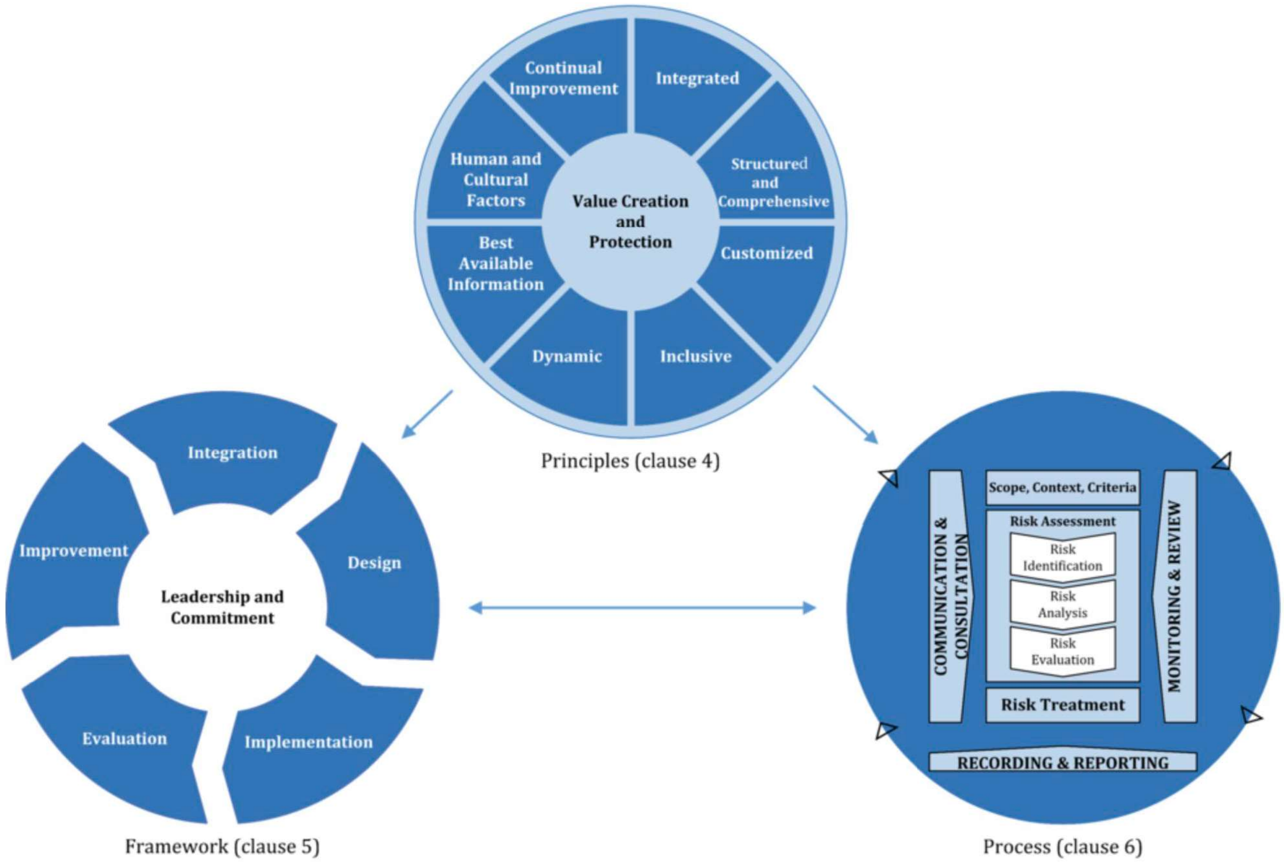
Historically much of the focus in risk management has been on managing financial risk. For instance, investors may need to determine their risk of incurring loss from a portfolio and underwriters need to establish the price at which to offer insurance. Approaches for managing risk need to help a decision-maker determine how likely a given risk is, and the consequences of the risk if it is realized. In making decisions, one needs to consider these factors, as well as their level of risk aversion.

Regarding the concept of risk aversion, if a decision-maker is risk-tolerant and simply trying to minimize economic losses, he or she would be indifferent between two risks with the same predicted loss: Risk A with a 1% chance of causing 90 fatalities; and Risk B with an 90%

chance of causing 1 fatality. However, if a decision-maker is risk-averse then he or she might prefer facing Risk B over Risk A given the maximum loss is much lower (1 life rather than 90). It is consistent with best practice to incorporate adjustments for risk aversion if the risks being considered have greatly different consequences, particularly if fatalities are considered as a potential consequence. The current state of the practice in managing financial risk incorporates consideration of the decision-maker's level of risk aversion (*1*).

The tools and techniques for managing financial risk are directly applicable to managing the risk of transportation project schedule and cost overruns. Many DOTs, including Caltrans, have adopted sophisticated approaches for managing these risks. *National Cooperative Highway Research Program (NCHRP) Report 658: Guidebook on Risk Analysis Tools and Management Practices to Control Transportation Project Costs (2)* provides guidance on managing the risk of project cost overruns including recommended processes for cost estimation, a framework for risk management, and example risk assessment tools and approaches. This report provides examples of specific approaches from agencies including Caltrans, Minnesota DOT, Pennsylvania DOT, and others.

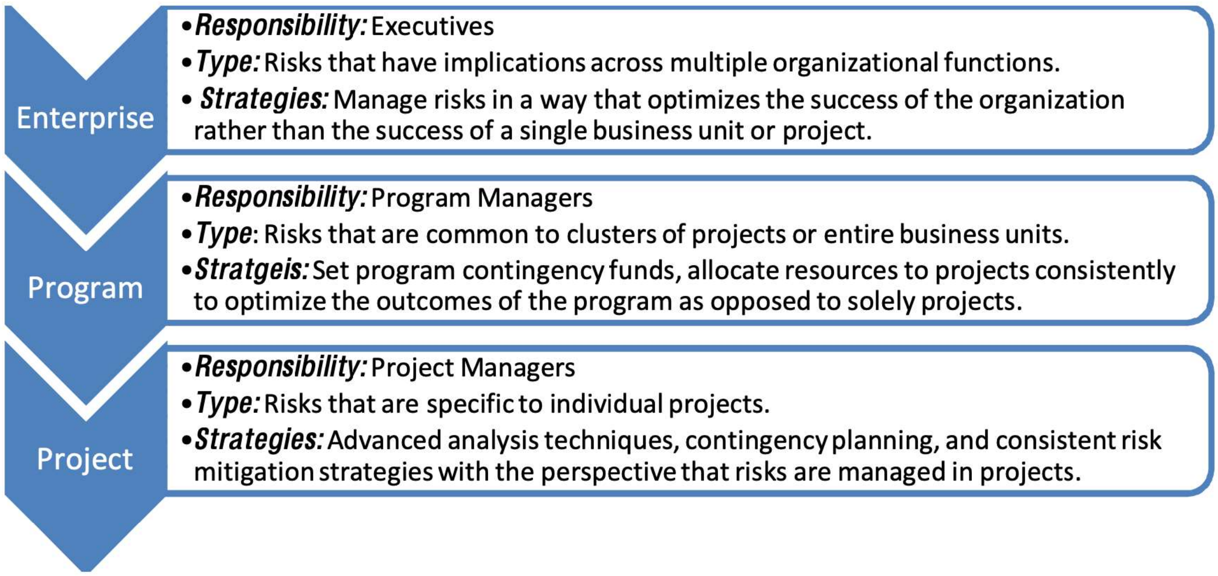
Risk management approaches have been applied to a broad range of different applications beyond managing financial risks. Further, in recent years different standards and professional organizations have developed risk management frameworks to help structure the identification, assessment, and response to risks across different areas of an organization. Perhaps the most established of these frameworks is International Standards Organization (ISO) Standard 31000 for Risk Management *(3)*. This standard was first published in 2009 and updated in 2018. ISO defines risk broadly as the "effect of uncertainty on objectives" and risk management as "coordinated activities to direct and control an organization with regard to risk." Figure 1, reproduced from ISO 31000, illustrates the guiding principles for risk management, the basic steps in the risk management process, and a framework for risk management. The process illustrated in the figure includes steps for risk assessment, treatment identification, and ongoing monitoring and reporting.



Source: ISO 31000 (3)

Figure 1. ISO 31000 Risk Management Principles, Framework and Process

U.S. transportation agencies have begun to establish risk management processes modeled on the ISO framework. The report *Executive Strategies for Risk Management by State Departments of Transportation (4)* present results of a survey of State DOTs on their risk management approaches, and recommends steps for establishing an enterprise risk management (ERM) approach based on ISO 31000. This report emphasizes the need to manage risk at multiple levels of the organization, including the enterprise, program and project levels. Figure 2, reproduced from this report, illustrates these levels. Based on the survey results the authors conclude that 13 State DOTs have approaches for managing risk at all three levels.



Source: Executive Strategies for Risk Management by State DOTs (4)
Figure 2. Relationship Between Enterprise, Program and Project Risks

Recently further work was performed to develop guidance for implementing risk management for State DOTs, resulting in publication of the *American Association of State Highway and Transportation Officials (AASHTO) Guide for Enterprise Risk Management (5)*. This guide describes how to apply the ISO framework to State DOTs, details the steps in implementing risk management, and provides examples of risk registers and other risk management tools.

Applications of Risk Management to TAM

Most TAM guidance presents risk management as an area that overlaps with TAM and/or as a TAM enabler. FHWA has published a series of five reports in the series *Risk-Based Transportation Asset Management* describing the application of the ISO 31000 risk management framework for supporting TAM (*6, 7, 8, 9, 10)*. These reports do not recommend any specific, quantitative approaches for assessing or prioritizing risk, but do provide examples of risk management approaches used by transportation agencies. Report 5 (*10*) in the series is notable with respect to the current effort, in that it summarizes approaches State DOTs have used to assess climate change, geologic hazard, seismic, and scour risk, including but not limited to examples from Caltrans, Washington State DOT (WSDOT), and Oregon DOT.

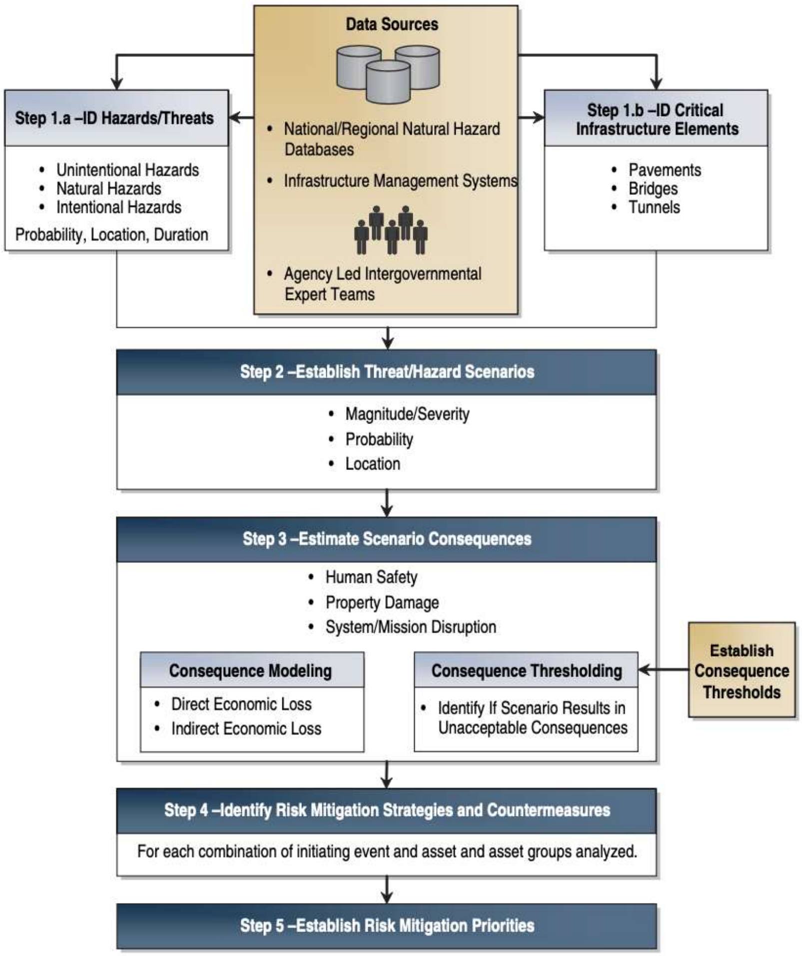
Moving Ahead for Progress in the 21st Century (MAP-21), enacted in 2012, requires that State DOTs develop risk-based transportation asset management plans (TAMPs) for their National Highway System (NHS) pavement and bridges. The FHWA guidance document *Incorporating Risk Management in to Transportation Asset Management Plans (11)* describes how to develop a TAMP that complies with the TAMP regulations initiated by

MAP-21. It describes how to use the ISO 31000 framework to identify risks, create a risk register, identify mitigation actions, and establish a plan for ongoing monitoring review. The most recent versions of the *AASHTO TAM Guide (12, 13)* describe risk management as an enabling process for TAM, and emphasize its importance. The 2011 Guide *(12)* presents examples drawn from the NCHRP 590 report described further below, as well as from other efforts to mitigate risks of bridge failures. The 2020 TAM Guide *(13)* presents examples of risk register development, as well as three examples in which risk is use to drive investment decisions:

- Caltrans' Seismic Risk Management Program established in the 1990's;
- Analysis of Harbor-Wide Barrier systems for the Boston area developed by the University of Massachusetts in 2018; and
- The risk management strategy used the Regional Municipality of Peel, which focuses on the risk a given asset will fail to meet its designated level of service.

Most examples of the application of risk in TAM either describe risk management broadly, as the above documents do, or focus on the assessment of specific risks (e.g., scour or seismic risks for bridges). However, there are several publications that describe quantitative risk assessment approaches applied to prioritizing investments for multiple types of risks and/or multiple asset classes. *NCHRP Report 590: Multi-Objective Optimization for Bridge Management Systems (14)* presents an approach for prioritizing bridge investments considering needs for asset preservation, functional improvement, and risk reduction. Risks considered include scour, fatigue/fracture critical bridges, earthquakes and other risks. The report describes prioritizing candidate investments based on overall utility, and presents a utility function and suggested weights for different objectives, including risk reduction. Also, it presents examples of how New York State DOT (NYSDOT) calculates vulnerability ratings for bridges considering risk of scour, fatigue, earthquakes, overloads, collisions and other "human-made" vulnerabilities.

NCHRP Report 632: As Asset-Management Framework for the Interstate Highway System (15) recommends an assessment process for consideration of risks to Interstate Highway System assets. It recommends incorporating risk mitigation actions into the overall resource allocation process. The idealized assessment process depicted in the report prioritizes risks based on predicted economic losses where sufficient data are available to support an assessment, or based on "consequence thresholding" (consideration of ranges of likelihood and consequence) where sufficient data are unavailable.



Source: NCHRP Report 632 (15)

Figure 3. TAM Risk Assessment Approach

The recently-published *NCHRP Report 903: Geotechnical Asset Management for Transportation Agencies (16)* presents a framework and tools for management of geotechnical assets that explicitly incorporates consideration of risk. This report is of particular relevance to the current effort given it provides a semi-quantitative approach for prioritizing asset investments across multiple asset classes and types or risk, including the some of the same assets and types of risks identified by Caltrans. The report discusses different causes of failures of geotechnical assets, including assets such as retaining walls, embankments, cut slopes, and constructed subgrades within the right-of-way or easement, as well as potential rock debris and landslide locations. The report includes a spreadsheet tool called the GAM Planner for inventorying assets, predicting future conditions, and prioritizing investments in geotechnical assets using a risk-based approach. The following are key elements of the GAM Planner model:

- Different vulnerabilities are combined to determine overall estimates of the likelihood and consequences of asset failure.
- The likelihood of failure is estimated by the asset type and asset condition. Different types may be defined to capture differences in failure rates between otherwise similar assets. Asset condition is specified on a five-point scale, with the failure rate defined for each condition.
- Two types of failure consequences are considered: safety consequences and mobility consequences. Each is specified on a five-point scale, and the two types of consequences are combined to determine an overall safety/mobility consequence level. Agency and user failure costs are specified by consequence level.
- An overall risk level and risk score are determined based on the condition and consequence level. These measures are predicted over time given a predicted budget for geotechnical assets.
- The optimal treatment for an asset is determined through solving a Markov Decision Model. The model yields the optimal treatment to take for each combination of condition and consequence level to minimize lifecycle agency and user costs. The modeling approach is similar to that developed previously in the Pontis Bridge Management System, except the model is solved for 25 different states (five condition levels x five consequence levels) rather than the five states considered in the Pontis models. The model also yields the increased lifecycle cost of deferring action.
- Treatments are prioritized with the objective of minimizing lifecycle costs. This is accomplished by choosing treatments in decreasing order of benefit cost ratio, calculated by dividing the lifecycle savings from performing the treatment (relative to deferral) by the treatment cost.

Figure 4 shows an example model from the GAM Planner illustrating specification of the model parameters for a given asset type and a table showing the optimal policy for each combination of condition and consequence level.

NCHRP Project 24-46 GAM Planner

Asset Model: NatHaz-Landslide-Example

Solve Model | Main Menu

MISCELLANEOUS PARAMETERS

Description: NatHaz-Landslide-Example
Discount Rate: 5%

TREATMENTS

ID	Description	Feasible	Annual Agency Co	Notes
1	Maintain	Yes	5,000	
2	Rehab	Yes	250,000	
3	Reconstruct	Yes	500,000	

PARAMETERS SPECIFIED BY OPERATIONS & MAINTENANCE CONDITION LEVEL

Risk Level	Do Minimum Cost Agency	User	Total	O&M Condition Level After	One-Year Probabilities for the Do-Minimum Action Stay the Same	Deteriorate	Med. Years to Deteriorate	Fail	Notes
1	0	0	0	N/A	96.0%	3.0%	17	1.0%	
2	500	0	500	1	93.0%	5.0%	10	2.0%	
3	2,500	0	2,500	2	90.0%	5.0%	7	5.0%	
4	5,000	0	5,000	2	50.0%	N/A	1	50.0%	

PARAMETERS SPECIFIED BY SAFETY & MOBILITY RISK LEVEL

Risk Level	Additional Annual Cost (Relative to Do Min Cost Above) Agency	User	Total	Annual Failure Risk for a New Asset	Unit Failure Cost Agency	User	Level Following Failure O&M Condition	fety/Mobility Risk	Notes
1	0	0	0	0.00%	4,000,000	5,000	1	1	
2	0	0	0	0.00%	4,000,000	5,000	1	2	
3	0	1,000	1,000	0.00%	4,000,000	25,000	1	3	
4	0	5,000	5,000	0.00%	4,000,000	50,000	1	4	
5	0	50,000	50,000	0.00%	4,000,000	500,000	1	5	

SOLUTION BY STATE

State	O&M Condition Level	Safety/Mobility Conseq. Level	Rec. Action	Desc.	Long-Term Cost	Benefit
1	1	1	1	Maintain	105,000	33,095
2	2	1	1	Maintain	105,000	71,690
3	3	1	1	Maintain	105,000	187,976
4	4	1	1	Maintain	105,000	1,904,762
5	5	1	4	Restore	4,105,000	0
6	1	2	1	Maintain	105,000	33,095
7	2	2	1	Maintain	105,000	71,690
8	3	2	1	Maintain	105,000	187,976
9	4	2	1	Maintain	105,000	1,904,762
10	5	2	4	Restore	4,105,000	0
11	1	3	1	Maintain	126,000	33,276
12	2	3	1	Maintain	126,000	72,052
13	3	3	1	Maintain	126,000	188,881
14	4	3	1	Maintain	126,000	1,913,810
15	5	3	4	Restore	4,145,000	0
16	1	4	1	Maintain	210,000	33,476
17	2	4	1	Maintain	210,000	72,452
18	3	4	1	Maintain	210,000	189,881
19	4	4	1	Maintain	210,000	1,923,810
20	5	4	4	Restore	4,250,000	0
21	1	5	3	Reconstruct	650,000	61,610
22	2	5	3	Reconstruct	650,000	104,672
23	3	5	3	Reconstruct	650,000	234,359
24	4	5	3	Reconstruct	650,000	2,152,166
25	5	5	4	Restore	5,119,048	0

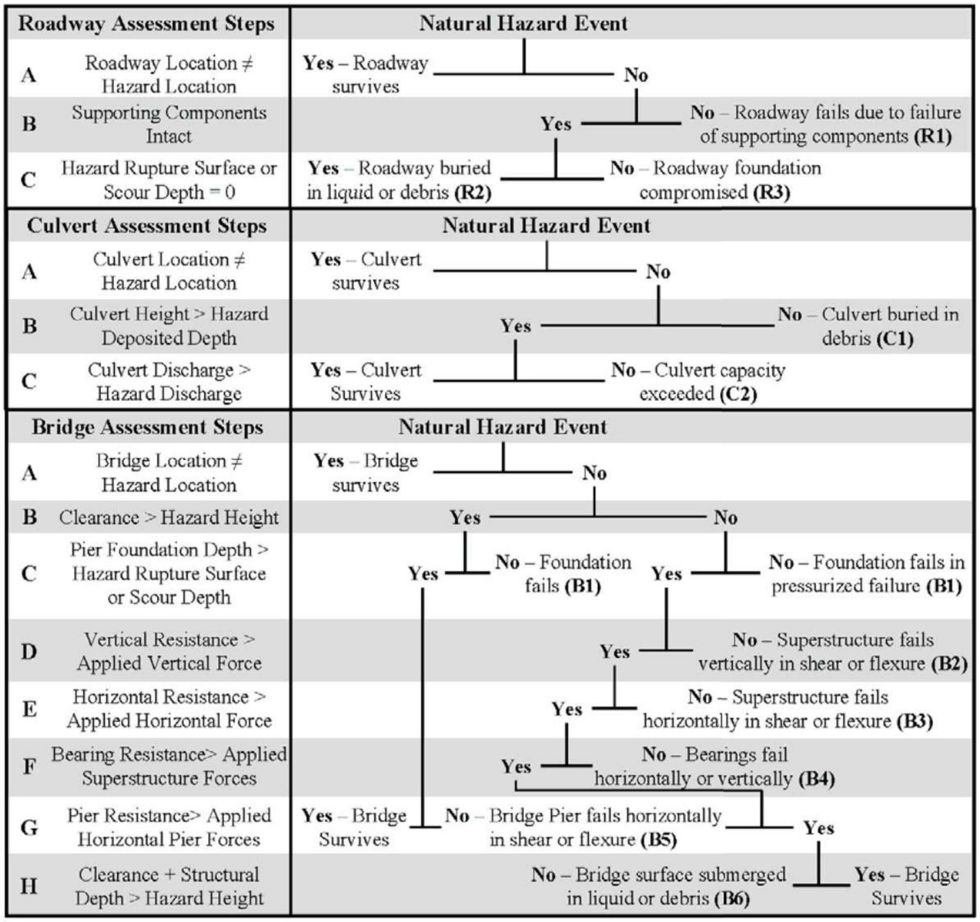
Figure 4. Example GAM Planner Model

The references above describe notable examples in which DOTs have employed quantitative, risk-based approaches to support investment decision across multiple types of risks and/or asset classes in the areas pertinent to the current effort. There are many additional examples in the literature in which risk-based approaches have been implemented or proposed. Examples in which investments are prioritized considering multiple asset classes and/or types of risk include, but are not limited to the following:

- Chang, et. al *(17)* present a framework for incorporating costs associated with seismic risk into a life cycle cost analysis for bridges.
- Ezell, et. al. *(18)* propose a probabilistic infrastructure risk analysis model developed for a water supply and treatment system considering interconnectedness between different system components.
- Hastak and Baim *(19)* identify risk factors that may impact management of roads, bridges, and subway stations.

- Salem, et. al. *(20)* describe calculation of pavement life cycle costs considering uncertainty in future pavement treatments.
- Birdsall and Haijdin *(21)* detail application of the NYSDOT qualitative bridge hydraulic vulnerability assessment approach to a set of three bridges in Switzerland, and contrast the results with application of a proposed quantitative assessment approach considering a range of additional vulnerabilities.
- Bründl, et. al. *(22)* describe a tool called EconoMe used in to calculate and communicate the level of risk from natural hazards in Switzerland. The tool the economic cost of different hazards, and the expected reduction in costs from different mitigation actions.
- Herrera, et. al. (*23*) summarize the results of the I-70 Corridor Risk & Resilience Pilot performed for Colorado DOT. The pilot is detailed in (*24*). In the pilot the Risk Analysis and Management for Critical Asset Protection (RAMCAP) Plus framework was used to identify vulnerabilities and evaluate mitigation options for the I-70 Interstate Highway System corridor.

Of these examples, three are of particular relevance to the current effort. Birdsall and Hajdin *(21)* demonstrate the application of a quantitative approach for assessing risk of avalanches, debris flows, floods, landslides, and rockfalls to bridges, roadways and culverts. The authors define a set of failure modes for each asset class, as illustrated in Figure 5 and demonstrate the prediction of economic losses for each failure mode. They conclude that while NYSDOT's approach has value for qualitatively assessing risk of bridge hydraulic failure, the more comprehensive framework the authors propose serves to "…illuminate previously undocumented highway and roadway risks that far exceed the previously documented bridge hydraulic-induced failure risks."



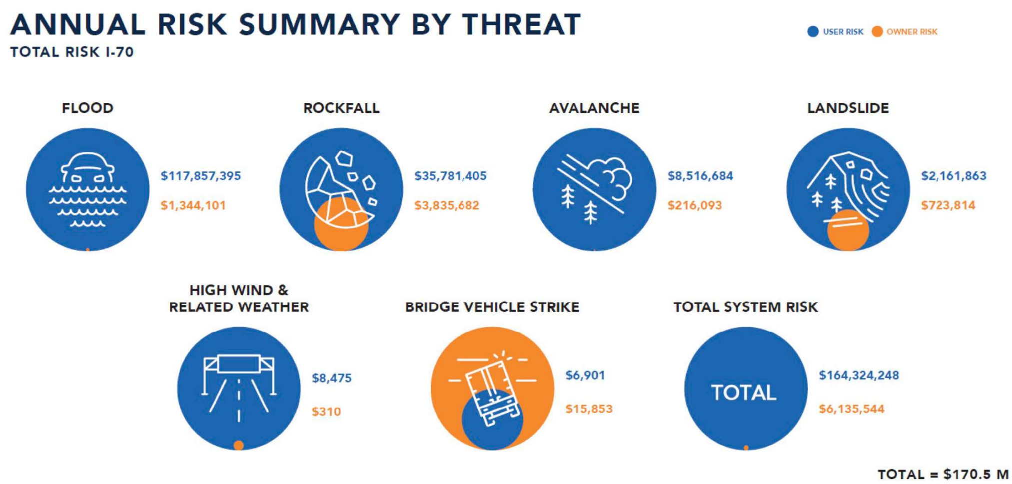
Source: Birdsall and Hajdin (21)

Figure 5. Example Roadway, Culvert and Bridge Failure Modes

Since completion of the work described in (*21*) the authors have continued to develop the concepts described in the paper further through two projects for the European Commission: SAFE-10-T (https://www.safe10tproject.eu/), which resulted in a risk-based decision support framework and software; and SAFEWAY (https://www.safeway-project.eu/en), in which the authors are enhancing a bridge management framework to include resilience.

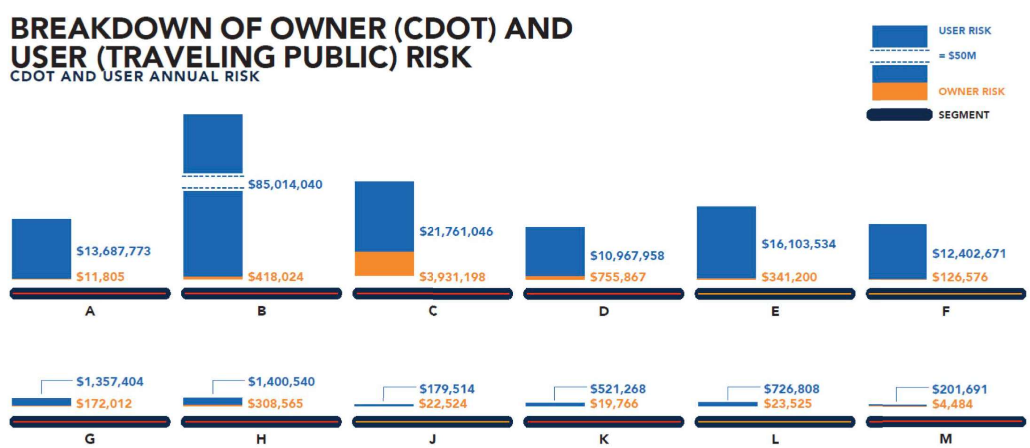
The EconoMe tool described in *(22)* has been used since 2008 to evaluate measures for public projects in Switzerland to mitigate risk of avalanches, landslides, rockfalls, floods, and debris flow. The tool predicts costs savings from reduced fatalities of these risks, demonstrating use of a quantitative risk management approach for prioritizing investments for multiple asset and risk types. Its analysis is based on the Swiss National Risk Concept for Natural Hazards (RIKO) framework. Following development of EconoMe further work was performed to apply the framework to the Swiss road network through efforts including development of a risk assessment tool called RoadRisk and supplemental research performed by Bernard, et. al. (*23*).

The I-70 pilot *(24, 25)* is notable as an example in which data from a vulnerability assessment similar to those performed by Caltrans is further quantified and used to inform development of mitigation alternatives. Figure 6, reproduced from the pilot report, shows the risk level along the corridor by type of risk, and Figure 7 shows the risk by corridor segment.



Source: AEM (25)

Figure 6. I-70 Risk by Type



Source: AEM (25)

Figure 7. I-70 Risk by Corridor Segment

Summary of Best Practices

The literature provides several examples in which public agencies have used information on risk to help prioritize asset investments across multiple asset classes and risk types. Below is a summary of best practices drawn from the review:

- ISO 31000 *(3)* provides an overall framework for risk management, and many U.S. agencies are in the process of implementing risk management practices consistent with this standard.
- Often qualitative approaches are used for performing an initial assessment of risk. For instance, many transportation agencies – including Caltrans – have developed risk registers in which qualitative assessments of risk likelihood and consequence are used to help identify high priority risks.
- In the examples in which risk is used to help prioritize asset investments, the level of risk should ideally be quantified by multiplying the likelihood of a given event by the economic consequences of the event's occurrence. The change in the level of risk resulting from a proposed treatment can then be used to help prioritize candidate investments. Examples of this approach are described in various examples cited above (*15, 17, 18, 21, 22, 23, 24, 25*).
- In some cases where quantitative data on risk likelihood and consequence are unavailable, prioritization approaches have been developed using qualitative approaches in which categories of likelihood and consequence are determined through expert judgement. Several NCHRP reports included in the review combine qualitatively-determined values of risk likelihood and consequence with quantitative prioritization approaches *(14, 15, 16)*. Altenbach *(26)* compares qualitative and quantitative approaches for risk assessment, and recommends using assigning a quantitative scale to categories of risk likelihood and consequence to facilitate quantitative assessment even when categories are established through expert judgement. This approach is illustrated in the I-70 pilot *(24, 25).*
- The most common types of consequences considered in the examples reviewed are costs to the agency of replacing failed assets and costs to users from detours. In some cases, safety risks are considered, but in others the general assumption is that a road or bridge is generally closed to avert loss of life, and that the major user impacts are from increased travel time and operating costs from the resulting detour.
- Risk aversion is a well-established (albeit much debated) concept in risk management (*1*), but is not addressed in the prioritization approaches reviewed, with the exception of *(22)*. Consideration of risk aversion is most important when comparing risks of greatly different likelihood and consequence.
- Often it is necessary to define design events to simplify the assessment process. This can be particularly important where there is deep uncertainty about the probability

of some event – e.g., the predicted level of sea level rise. In some cases, different scenarios are defined, and the assessment is performed for each scenario. This approach is used in the case of the harbor barrier assessment described in *(13)*.

3. Review of Caltrans Data

Overview

Caltrans has previously performed significant work to assess risk, resulting in data and analyses in each of the risk areas addressed by the current project. This includes efforts to prioritize seismic retrofit needs, assess scour vulnerability for bridges, assess landslide vulnerability, and develop of climate change vulnerability assessments for each Caltrans district. In this task the research team performed an initial review of the available data.

At Caltrans' direction, the research team focused its review on the data and assessments for two districts: District 1 and District 4. District 1 is located along the Pacific Ocean in the northwest corner of the state. The geography of District 1 features rocky coastline, redwood forests of the Coastal Mountain Range, and low-lying marshes. District 4 lies south of District 1, and is also located along the Pacific Ocean. It includes nine counties in the San Francisco Bay Area. It is a major population center and employment area. Also, it is a freight and transport hub with assets that provide critical connections to the rest of the state. The geography of the district varies between coastline, tidal marshes, and mountains.

The following sections describe the review of seismic, scour, landslide and climate vulnerability data for each district. The final section discusses implications of the review for the effort to develop a statewide risk score.

Seismic Vulnerability

Caltrans calculates a seismic vulnerability score for each of the bridges on the SHS as part of its Seismic Safety Retrofit Program. This program was initiated following the Loma Prieta Earthquake in 1989, which resulted in multiple bridge failures and 44 fatalities on the SHS. Caltrans' approach is summarized in a case study in *(13).* The initial scoring approach, subsequent revisions, and current approach are detailed in a recent Caltrans report *(27)*.

As documented in (*27*), the seismic risk score is calculated considering the likelihood of an earthquake at the bridge site, the vulnerability of the bridge to collapse in the event of an earthquake, and the impact of a collapse considering the traffic using the bridge and detour distance in the event of a collapse. The score is the product of three criteria: vulnerability; hazard; and impact. Table 1 lists the attributes of each criterion and notes how they are used.

Table 1. Caltrans Seismic Score Criteria and Attributes

Criterion	Attribute	Notes
Vulnerability	Very Brittle Score Brittle Score Nonductile Score Other Vulnerabilities Score Poor Details Score	Calculated based on number of design details contributing to each score using the sum of squares method with different scoring approaches used considering degree of soil liquefaction
Hazard	Spectral Displacement Soil Factor Remaining Life Factor Net Offset	Calculated by multiplying the first three variables and adding the offset to account for proximity to a fault
Impact	Average Daily Traffic (ADT) On Structure Detour Length	Proportional to the product of ADT and Detour Length, with a transformation to limit the factor to a range of 0 to 1

To support the review Caltrans provided a spreadsheet listing 317 seismically vulnerable bridges in Districts 1 and 4: 60 in District 1 and 257 in District 4. Also, Caltrans provided an additional spreadsheet with supplemental details showing the hazard, vulnerability and impact scores calculated in 2015. The scores range from a minimum of 0.2 to a maximum of 1.0. In total, 22 bridges (9 in District 1 and 12 in District 4) have a score of 1.0, indicating they have highest priority for a seismic retrofit.

Scour Vulnerability

Caltrans calculates scour vulnerability as required based on the National Bridge Inspection Standards (NBIS) and documented in the *Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges (28)*. As specified in this document, Item 113 – Scour Critical Bridges of the National Bridge Inventory (NBI) summarizes the vulnerability of each bridge on the NBI to scour. If Item 113 has a value of 0 to 3 then the bridge is deemed to be "scour critical." Scour assessments are performed as detailed in *(29)*.

Caltrans provided data on Item 113 for each of the bridges in District 1 and 4. The data provided includes scour critical codes by year from 2008 to 2019. Table 2 shows the values defined for Item 113 and the count of bridges with each value based on data provided by Caltrans. As shown in the table, 14 bridges in the two districts (5 in District 1 and 9 in District 4) are open but classified as scour critical. An additional 13 bridges (2 in District 1 and 11 in District 4) are closed.

Table 2. Scour Critical Codes and Results for Districts 1 and 4

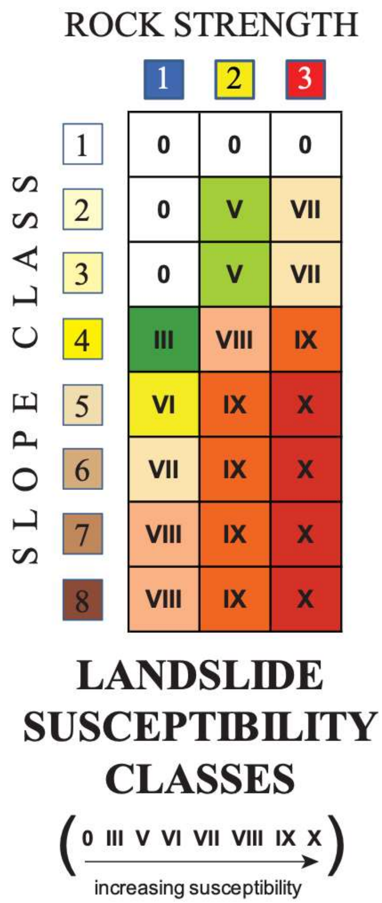
Code	Description	District 1 Count	District 4 Count
N	Bridge Not Over Waterway	163	1,422
U	Bridge with “unknown” foundation that has not been evaluated for scour.	2	4
T	Bridge over "tidal" waters that has not been evaluated for scour, but considered low risk. Bridge will be monitored with regular inspection cycle and with appropriate underwater inspections. ("Unknown" foundations in "tidal" waters should be coded U.)	0	0
9	Bridge foundations (including piles) on dry land well above flood water elevations.	4	15
8	Bridge foundations determined to be stable for the assessed or calculated scour condition. Scour is determined to be above top of footing by assessment (i.e., bridge foundations are on rock formations that have been determined to resist scour within the service life of the bridge), by calculation or by installation of properly designed countermeasures.	139	317
7	Countermeasures have been installed to mitigate an existing problem with scour and to reduce the risk of bridge failure during a flood event.	3	1
6	Scour calculation/evaluation has not been made. (Use only to describe case where bridge has not yet been evaluated for scour potential.)	0	2
5	Bridge foundations determined to be stable for assessed or calculated scour condition. Scour is determined to be within the limits of footing or piles by assessment (i.e., bridge foundations are on rock formations that have been determined to resist scour within the service life of the bridge), by	141	168

Code	Description	District 1 Count	District 4 Count
	calculations or by installation of properly designed countermeasures.		
4	Bridge foundations determined to be stable for assessed or calculated scour conditions; field review indicates action is required to protect exposed foundations.	5	11
3	Bridge is scour critical; bridge foundations determined to be unstable for assessed or calculated scour conditions.	5	8
2	Bridge is scour critical; field review indicates that extensive scour has occurred at bridge foundations.	0	1
1	Bridge is scour critical; field review indicates that failure of piers/abutments is imminent. Bridge is closed to traffic.	0	0
0	Bridge is scour critical. Bridge has failed and is closed to traffic.	2	11

Landslide and Rockfall Vulnerability

The California Geologic Survey (CGS) maintains baseline data on the geology of California through its Regional Geologic (and Landslide) Mapping Program. Through this program CGS maintains a web-based inventory of landslide locations at https://maps.conservation.ca.gov/cgs/lsi/app/. Also, CGS calculates landslide vulnerability for locations throughout the state. Figure 8 summarizes the ten landslide susceptibility classes defined by CGS as a function of slope class and rock strength. These are described further in *(30)*.

Caltrans provided the research team with an inventory of highway segments for Districts 1 and 4. The inventory includes 11,708 highway segments representing approximately 2,391 road miles. The segments average 0.2 miles in length. For each segment Caltrans has determined the minimum, maximum, median and mean landslide susceptibility using the CGS classes. Nearly half of the segments (992 road miles) have some portion of the segment in the highest (most susceptible) class (Class 10). A small number of segments (27 road miles) have a median class value of 10, indicating at least half of the segment is in this class.



Source: Wills, et. al. (30)
Figure 8. Landslide Susceptibility Classes

Specific to rockfall hazards, the Caltrans Geotechnical Manual documents the department standard of practice for rockfall (*31*). Per the Caltrans definition, rockfall is "*the movement of rock of any size from a cliff or slope that is steep enough for the rock to move down slope. Movement may involve any combination of free falling, bouncing, rolling, or sliding. Rockfall may involve more than one rock, but excludes slope failures involving large volumes of rock, such as rock avalanches or landslides*." Thus, rockfall is considered to be a specific type of slope failure that is generally considered to be a single rock or limited volume of rocks.

The Caltrans Geotechnical Manual indicates that rockfall sites should be analyzed using established procedures for a Rockfall Hazard Rating System (RHRS), which is a planning process for obtaining comparable information among a series of slopes for use in safety improvements and reductions in maintenance and other operational costs. The RHRS process relies on a series of individual category scores that subjectively rate parameters related to geologic character of a slope, hazard conditions, and safety consequence to produce a total score that is the sum of each individual input. The individual inputs are selected from an exponential scale of category values – 3, 9, 27, and 81 – and the total score that results from summing the individual inputs represents a blended qualitative assessment of hazard likelihood, safety consequence, and geological measures. Where available, the individual inputs into the RHRS process that represent likelihood of an event can be translated into a structured risk-based assessment process for treating rockfall sites in the context of asset management and other performance objectives.

Climate Change Vulnerability

Caltrans has prepared climate change vulnerability reports for each of its twelve districts. For each district Caltrans has prepared a summary report that provides the high-level results of the assessment, a technical report that includes more details on the approach used to conduct the assessment, and an interactive map that shows the areas impacted by various climate stressors or hazards.

The technical reports for each district include a description of all the climate stressors (e.g., temperature, precipitation, wildfire, sea level rise, storm surge, and cliff retreat). These reports also include the assessment results of which areas are most vulnerable to the different climate stressors.

In general, the vulnerability assessments report that the following climate trends are expected in various regions of the state that will impact transportation infrastructure:

- More severe droughts will lead to less snowpack and changes in water availability;
- Rising sea levels will lead to more severe storm impacts and an increase in coastal erosion;
- Temperatures will increase and there will be more frequent and longer heat waves; and
- Wildfire seasons will last longer and be more severe.

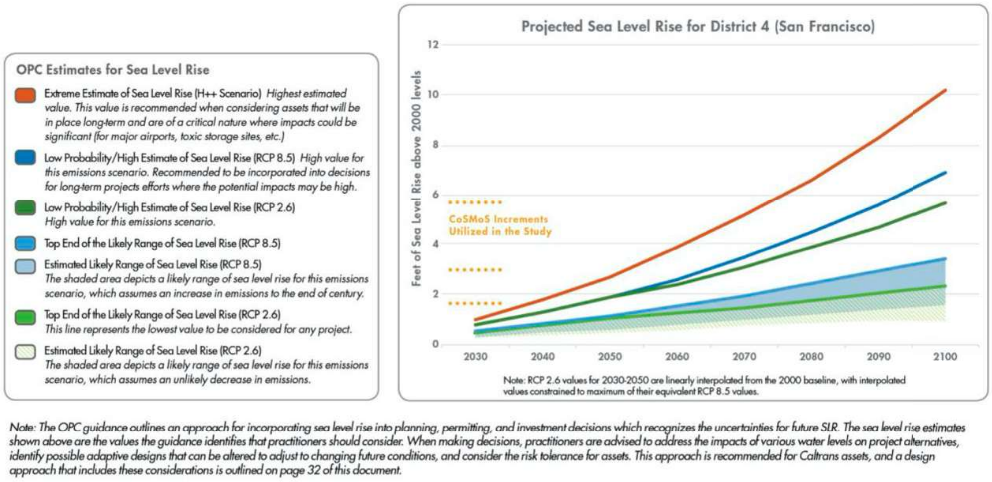
The vulnerability assessments focus on different climate stressors and their potential impacts on the SHS. Table 3 lists these stressors and notes the impacts found in the District 1 and 4 assessments.

Table 3. Climate Stressors and Impacts

Climate Stressor	District 1 Impacts	District 4 Impacts
Temperature	Rising temperatures, especially at higher elevations, combined with changing snowmelt patterns may cause tree mortality in the area. Rising temperatures also have impacts on pavement design as high	Rising temperatures will have an impact on pavement design and will determine pavement mixes. Extreme heat events will increase maintenance activities due to material damage. The need to

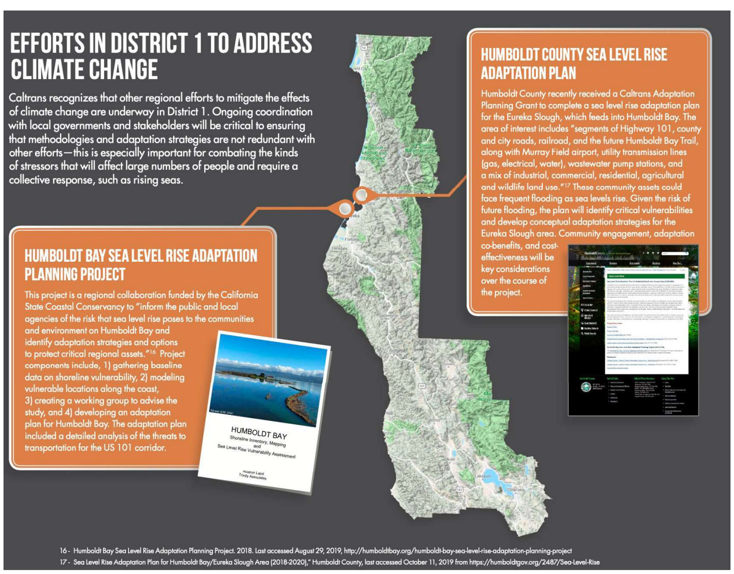
Climate Stressor	District 1 Impacts	District 4 Impacts
	heat can affect pavement quality and lifespan.	protect worker safety from high heat can cause changes in scheduling as well.
Precipitation	Increasingly heavy precipitation increases the risk of floods, mudslides, and landslides which causes delays and road closures in the region.	Increasingly heavy precipitation increases the risk of floods, mudslides, and landslides which causes delays and road closures in the region.
Wildfire	High temperatures and drought increase the risk of wildfire. As a result, road closures and infrastructure damage are more and more likely.	Road closures due to wildfires cause traffic, roadblocks, and detours on the roads in the District.
Sea Level Rise	Higher sea levels cause increased and more severe flooding along the coast. This impacts coastal infrastructure, causing damage to substructures and erosion at the shoreline.	Higher tide events are impacting coastal infrastructure, causing flooding along key areas of the District.
Storm Surge	Similar to sea level rise, high winds and precipitation can cause damage to coastal infrastructure. Erosion, landslides, shoreline retreat, and increased flooding are all possible with storm surge events.	Sea level rise, in addition to storm surge, contribute to the high levels of flooding in the District.
Cliff Retreat	The flooding and resulting erosion that is occurring at increased frequency have negative impacts to roads along the coast.	N/A

The assessments are extremely valuable as a reference for predictions of future climate trends. Figure 9, reproduced from the District 4 assessment shows an example of this, summarizing Ocean Protection Council (OPC) guidance on predicted sea level rise. The assessments also provide data on changes in temperature, wildfire vulnerability, precipitation, and flood potential.



Source: District 4 Vulnerability Assessment Technical Report (32)
Figure 9. OPC Guidance on Sea Level Rise

The assessments further describe work each district is performing to address climate change vulnerability. For instance, Figure 10 shows examples of two other adaption plans underway in the district.



Source: District 1 Vulnerability Assessment Summary Report (33)
Figure 10. Example Efforts to Address Climate Change in District 1

The assessments for both districts describe that the current focus in each district is on identifying the vulnerabilities. The assessments describe that further work will be required to determine how to mitigate climate-related risks and prioritize treatments.

In addition to preparing the climate change vulnerability reports, Caltrans has performed supplemental analysis to evaluate the impacts from the combination of sea level rise inundation and storm surge. To support this analysis Caltrans has projected, by decade, whether or not each highway section is expected to be inundated. The assumption is that facilities impacted will no longer be in service due to permanent inundation or other impacts resulting from the rising sea level. The initial analysis for District 4 is described in *(34).*

Discussion

The data provided by Caltrans for Districts 1 and 4 demonstrate that detailed information is available with respect to each of the risk areas considered as part of the project. The review of available data has the following implications for development of a statewide risk score:

- The available data can be used to help estimate event likelihood for all of the types of risks considered for the current effort - Bridge Seismic Hazards, Bridge Scour, Landslide and Rockfall Hazards, and Climate Change Vulnerability.
- The seismic vulnerability score combines consideration of likelihood and consequence. Ideally the scoring approach should separate these components and use a consistent approach for impact calculation across different types of risks. Note that the hazard and vulnerability components of the seismic score are a proxy for likelihood.
- The scour critical item calculated for the NBI provides an indication of the current scour vulnerability of a bridge, but does not reflect potential future scour vulnerability – e.g., if the bridge is subject to increased risk of flooding as a result of climate change. While the available data can be used as-is to facilitate calculation of a risk score, ideally this item would be supplemented with additional information to better characterize future scour risk.
- Regarding landslide vulnerability, further consideration is merited of what specific value to use to best characterize the vulnerability of a highway segment – e.g., the mean, median or maximum landslide susceptibility class.
- The climate changes assessments describe specific climate stressors and how affect the SHS. Thus, the assessments can be used to relate climate change to specific risks to transportation assets (e.g., flooding) that are made more likely as a result of climate change.
- The events described in the climate change assessments, both actual examples and modeled future events, can be used to determine the scenarios and/or design events to be considered in determining event likelihood and consequence.

- Caltrans has provided projections, by decade, for which highway sections are expected to be inundated. This information can be used to assess risk of sea level rise and storm surge.

4. Risk Scale Approach Details

Overview

This section describes the proposed approach for calculating a risk score incorporating Bridge Seismic Hazards, Bridge Scour, Landslide and Rockfall Hazards, and Climate Change Vulnerability. For each of these risks three types of impacts are considered: agency; safety; and mobility impacts. The risk score for a given type of risk and impact is the product of the likelihood and consequence or impact, with adjustments to account for risk tolerance, perceptions of different risks, and other factors. The overall risk score for a given location is calculated as illustrated in Equation 1:

$$R = \sum_i f_i P_i \left(I_{i,a} + I_{i,s} + I_{i,m} \right) \qquad (1)$$

where:

i = index indicating the type of risk,
1=bridge seismic hazards
2=bridge scour
3=rockfall hazards
4=climate change vulnerability
R = overall risk score
R_i = risk score for risk of type i
f_i = adjustment factor for risk of type i
P_i = annualized likelihood of risk i occurring
$I_{i,a}$ = agency impact of risk i occurring
$I_{i,s}$ = safety impact of risk i occurring
$I_{i,m}$ = mobility impact of risk i occurring

Note that seismic, scour, and rockfall risk are all treated in a similar manner. The likelihood of the risk occurring (absent mitigation) is assumed to be the same each year. Climate change vulnerability is different. Caltrans has projected what highway sections will be inundation by seawater given the best available information on sea level rise and storm surge. The probability of inundation occurring is 100% for these sections, but inundation is predicted to occur at different times for different sections. Thus, the probability of inundation is assumed to be either 0% or 100%, but the probability is adjusted to account for when inundation is predicted to occur.

The following subsections further describe the calculation of event likelihood for each risk type, and the calculation of impacts.

Risk Likelihood

For each type of risk, it is necessary to establish the likelihood the risk will occur. An annualized probability is used for the sake of consistency between different risks, with further adjustment for inundation risk that will occur beginning at a future point. In concept the likelihood of a risk occurring is the joint probability of hazard and vulnerability, where the hazard probability represents the likelihood a given event occurs, and the vulnerability represents the likelihood that an impact is realized as a result of the event. For instance, in the case of seismic risk it is necessary to consider both the likelihood an earthquake will occur – hazard – and that a given bridge may be damaged as a result – vulnerability. The approach for estimating overall likelihood addressing hazard and vulnerability is discussed below for each type of risk.

Bridge Seismic Hazards

The approach to assessing risk of bridge seismic hazards relies heavily on the index developed by Caltrans for use in prioritizing bridge seismic improvement work. While this index does not represent a probability, for purposes of this research and its broader goal it is recommended that the likelihood be determined as follows:

$$P_1 = cHV_{norm} \qquad (2)$$

where:

P_1 = average annual likelihood of a seismic hazard resulting in bridge closure occurring at a given location

c = seismic calibration factor

HV_{norm} = normalized product of hazard and vulnerability indices, calculated by Caltrans as described in *(27)*

This approach assumes that the score calculated by the Caltrans Office of Earthquake Engineering will be roughly proportional to the likelihood of bridge closure due to seismic events. However, the score is normalized on a scale of 0 to 1 rather than to the actual likelihood of an event occurring. Thus, an adjustment factor is needed to rescale the likelihood to a one-year probability to facilitate comparisons with other risks. An initial value of 0.013 (1/75) was recommended by Caltrans for *c* pending further research. This represents the assumed seismic life of a bridge of 75 years. Note the U.S. Geological Society (USGS) that the average repeat time in the California region is 13 years for an earthquake with a magnitude of 7 or greater on the Richter Scale *(35)*, though any given earthquake would impact only a portion of the bridges in the state.

Further research is recommended to better relate the *HV* values calculated by Caltrans to the likelihood of seismic hazard. This issue is discussed in Section 6.

Bridge Scour

The approach to assessing risk of bridge closure due to scour relies upon the bridge scour rating, NBI Item 113. Table 3 recommends values to use for P_2, the one-year probability of bridge closure or failure due to scour, based on this item. There is uncertainty with using the NBI rating as it provides an incomplete picture of the actual vulnerability of a bridge to scour. Updated values for P_2 could be determined with additional research regarding sensitivity of bridges to scour, as discussed further in Section 6.

In assigning the NBI Item 113 values, bridges are evaluated for scour potential based on the 100-year flood event. For instance, if the scour associated with this event causes instability, the bridge is coded as a 3. However, it is possible that the 10, 25 or 50-year event could also cause the bridge to become unstable. This measure of vulnerability is not captured in the 113 codes and is another challenge with using the rating. In addition, it is recognized that increasing levels of flooding do not always lead to increased scour; in fact, in some instances a lower frequency event can produce more scour. With additional research, updated values for P_2 could take into account an evaluation of bridges for multiple events ranging from smaller events up to the design flood event.

Table 3. Scour Critical Codes and Recommended Probabilities

Code	Description	Recommended Value for *P*	Note
U	Bridge with "unknown" foundation that has not been evaluated for scour.	0.01	Failure is uncertain due to unknown issues with the bridge – assumed to fail with frequency of once every 100 years.
8	Bridge foundations determined to be stable for the assessed or calculated scour condition. Scour is determined to be above top of footing by assessment (i.e., bridge foundations are on rock formations that have been determined to resist scour within the service life of the bridge), by calculation or by installation of properly designed countermeasures.	0.0025	Failure is unlikely – assumed to occur with frequency of once every 400 years.
7	Countermeasures have been installed to mitigate an existing	0.01	Failure is dependent on the integrity of the

Code	Description	Recommended Value for *P*	Note
	problem with scour and to reduce the risk of bridge failure during a flood event.		countermeasure – assumed to occur with frequency of once every 100 years.
5	Bridge foundations determined to be stable for assessed or calculated scour condition. Scour is determined to be within the limits of footing or piles by assessment (i.e., bridge foundations are on rock formations that have been determined to resist scour within the service life of the bridge), by calculations or by installation of properly designed countermeasures.	0.005	Failure is unlikely, but possible – assumed to occur with frequency of once every 200 years.
4	Bridge foundations determined to be stable for assessed or calculated scour conditions; field review indicates action is required to protect exposed foundations.	0.005	Failure is unlikely, but possible – assumed to occur with frequency of once every 200 years.
3	Bridge is scour critical; bridge foundations determined to be unstable for assessed or calculated scour conditions.	0.02	Closure or failure likely in the event of a 50-year flood
2	Bridge is scour critical; field review indicates that extensive scour has occurred at bridge foundations.	0.5	Closure or failure highly likely
1	Bridge is scour critical; field review indicates that failure of piers/abutments is imminent. Bridge is closed to traffic.	1.0	Bridge has already been closed
0	Bridge is scour critical. Bridge has failed and is closed to traffic.	1.0	Bridge has already failed

Rockfall and Landslide Hazards

In considering rockfall and landslide hazards, it is important to note that there are several types of closely related geohazards that Caltrans may need to evaluate. Strictly speaking, the methodology described here is intended to address a broad category of multiple slope hazards, but it is designed such that it can be refined for greater precision within a specific geohazard type.

Note that rockfall consists of the detachment, sliding, rolling, and bouncing of individual rock fragments dislodged from an upslope source *(36)*. Rockfall is a common hazard below natural cliffs associated with bedrock outcrops, steep natural slopes with boulders or talus surfaces, and highway road cuts into soil and bedrock materials (a form of geotechnical asset). The volume of a rockfall event can be relatively small, even an individual rock; however, rock fragments can travel at rapid velocities and thus the energy on impact with the roadway or vehicle is high.

The term “landslide” describes a variety of gravity driven movement of soil, rock and/or artificial fill that travel downslope as falls, topples, slides, spreads and/or flows *(36, 37, 38)*. The following types of landslides may impact Caltrans assets:

- Deep-seated landslide: a moving mass of soil and/or rock with sliding surface depth that is greater than 10 to 15 feet below the ground surface. Deep-seated landslides can result in relatively large volume slides that extend beyond the right of way (ROW). The rate of ground surface movement for these landslides often ranges from inches to feet per year creating recurring distress to pavement and other assets, although movement rates can accelerate and cause substantial damage in a period of hours or days.

- Shallow landslide: a mass of moving soil and occasionally rock with a typical maximum sliding depth that is less than 15 feet deep. Often, shallow landslides are associated with deteriorating embankments or natural soil slips within the ROW. Similar to deep-seated landslides, the movement rates are on the order of inches to feet per year; however, these slides also can suddenly accelerate resulting in complete slide failure within hours or days.

- A debris flow, as defined by Hungr, et al. *(36)*, is a very rapid, channelized flow of saturated soil and debris. Debris flows originate from source areas where the debris is mobilized by the influx of ground- or surface water, often during intense or prolonged rainfall periods. The event becomes fluid (liquefies) shortly after the onset of movement and begins to flow downstream increasing in volume by entraining additional water and channel debris. The mobilization and travel of debris flows into the Caltrans ROW can result in roadway washouts or deposition of large volumes of soil, rock, and debris on the roadway.

- A rock slide involves the detachment and downhill movement of a large volume of rock material, often from an exposed bedrock outcropping. The failure characteristics of rock slides can be similar to deep-seated landslides. Rock slides differ from rockfall in volume of material and can range from 30 cubic yards to several thousand cubic yards. While rockslides may exhibit creep or slow behavior over time that causes recurring distress to Caltrans assets, the rock mass also can fail further in brittle failure mode that results in a very rapid flow of rock debris down a steep slope.

To establish the overall probability P_3 of rockfall or other geohazard, it is necessary to determine the joint probability of the hazard event occurring and that the hazard, if it occurs, impacts a Caltrans asset. These probabilities are termed the event occurrence probability, P_H, and the spatial probability, $P_{S|H}$.

While methods exist for estimating both event occurrence and spatial probabilities, the inputs and analysis are impractical to scale to a statewide level without a substantial effort and investment. To estimate risk using the readily-available, existing information, the deep landslide susceptibility categories described in Section 3 are used to establish event occurrence probability, and the spatial probability is assumed to be 1.

For the purpose of developing an initial estimate of P_3, the defined classes for landslide susceptibility were grouped into 5 bins. The thresholds for each bin were established based on geotechnical judgement, and based on assumption that in the highest susceptibility class landslides occur on a near annual basis. Further research is recommended to review the categories and definitions presented in the table, and calibrate these based on available slope hazard performance data.

Table 4. Landslide Susceptibility Classes and Recommended Probabilities

Parameter	Negligible	Low	Moderate	High	Very High
Landslide Susceptibility Class	Class 0, I, II	Classes III, IV, V	Classes VI, VII, VIII	Class IX	Class X
Approximate Return Period	≥1000 years	100 to 1000 years	10 to 100 years	1 to 10 years	1 year or less
Descriptive Text	Event very unlikely to occur during a 100-year period	Event unlikely to occur during a 100-year period	Event possible during a 100-year period	Event typically occurs every few years	Event may occur at least once per year
Recommended Value for *P*	0.001	0.002	0.020	0.500	1.000

A key assumption of the existing landslide susceptibility classes is that weak rocks and steep slopes are more likely to generate landslides. The susceptibility assessment presented in the map does not consider triggers for landslides, such as precipitation influences, earthquakes, and slope modifications such as road cuts. Also, the defined classes address only deep-seated slides (e.g., slide planes deeper than 10 to 15 feet deep), meaning other slope hazards such as shallow landslides, debris flows, and rockfall are not specifically reported in the results. Nonetheless, the susceptibility mapping could be considered a surrogate for the debris flow hazard when linked with culvert drainage assets, as debris flows are more likely to occur during intense runoff from steep terrain with weak bedrock and soil. In addition, the proposed approach could be further extended at a later time to address additional geohazards. See Section 6 for further discussion on the limitations of the data and susceptibility mapping.

Climate Change

As discussed in Section 3, there are many potential impacts from climate change to Caltrans assets. In particular, climate change may increase the likelihood of scour or geohazards as a result of increased flooding. Here the inundation of roads caused by sea level rise and storm surge is treated as a distinct risk, while other impacts of climate change are addressed where applicable as part of each other type of risk. This is consistent with the approach followed by the Caltrans Asset Management Office (*34*).

For the purpose of calculating a risk score, P_4, the probability of inundation, is calculated as the probability that a given location will be subject to inundation as a result of sea level rise, discounted for when inundation is predicted to occur. With this adjustment, the probability term can be compared with the annualized probabilities for other risks that are assumed to have constant probability.

Values for P_4 can be calculated given the discount rate and number of years until inundation is predicted to occur. Given this data, the value for P_4 is calculated as:

$$P_4 = \frac{1}{(1+r)^n} \qquad (3)$$

where:

r = discount rate
n = number of years until inundation is predicted

The critical parameter in the calculation is the estimated years until inundation occurs, which must be determined through a separate analysis. This separate analysis takes into account the hazard (the likelihood that sea level rise will exceed a specified threshold) and vulnerability (the likelihood the facility will be inundated given a specified level of sea level rise). The discount rate is used to convert this parameter into a time-adjusted probability.

Agency Impacts

All of the different risks are expected to result in an agency impact. This impact is assumed to be proportional to the cost of repairing or reconstructing the asset, where needed, and any other agency costs associated with occurrence of the specified risk. The agency impact for a given location is calculated as shown below:

$$I_{i,a} = MC_i + RC_i \qquad (4)$$

where:

MC_i = average maintenance cost for risk of type i
RC_i = average rehabilitation/reconstruction cost for risk of type i

In the case of seismic and scour risks, the agency impact is typically 2-3 times the bridge replacement cost. For rockfall and landslide risk there can be a significant maintenance cost. An individual event typically does not necessitate reconstruction of the road. In this case the rehabilitation cost should represent the cost of substantially mitigating future rockfalls or landslides at the location. Inundation of a road is assumed to require reconstruction at a higher elevation.

Safety Impacts

The safety impact of a risk is assumed to be proportional to the crash costs predicted to result from the event, accounting for fatalities, injuries, and property damage only crashes. Safety impacts are estimated by first determining how many vehicles are likely to be directly exposed to the event, and then determining the likelihood of crashes of each type for each exposed vehicle, multiplying each probability by the corresponding cost. This is represented by the following equation:

$$I_{i,s} = \frac{L*ADT}{24*S}(C_p L_{i,p} + C_n L_{i,n} + C_f L_{i,f}) \qquad (5)$$

where:

L = location road length in miles
ADT = average daily traffic
S = average operating speed
C_p = cost per property damage only crash
$L_{i,p}$ = probability a vehicle exposed to risk *i* will suffer a property damage only crash
C_n = cost per injury
$L_{i,n}$ = probability a vehicle exposed to risk *i* will suffer an injury

C_f = cost per fatality
$L_{i,f}$ = probability a vehicle exposed to risk *i* will suffer a fatality

Mobility Impacts

All of the events considered may result in mobility impacts. These are assumed to be proportional to the increased operating and travel time costs resulting from a risk. Each event is assumed to cause detours of traffic on a bridge or road, resulting in increased travel time and operating costs. This cost may be expressed as follow:

$$I_{i,m} = ID * ADT\left((1 - PT/100)\left(\frac{DL}{DS}HC_a + DL * VC_a\right) + PT/100\left(\frac{DL}{DS}HC_t + DL * VC_t\right)\right) \quad (6)$$

where:

ID = incident duration, days
PT= percent trucks
DL= detour length in miles
DS= detour speed in miles per hour
HC_a= cost per vehicle hour, autos
HC_t= cost per vehicle hour, trucks
VC_a= cost per vehicle mile, autos
VC_t= cost per vehicle mile, trucks

Note the following regarding the equation:

- The equation addresses increased travel time and operating costs for cars and trucks.
- Ideally the detour distance should represent the increased distance resulting from the detour.
- The cost per vehicle hour should be calculated considering average vehicle occupancy.
- The cost per vehicle mile includes vehicle operating costs, and may include additional costs to society from increased emissions.

Additional Considerations

Below are other important considerations in calculating the risk score:

- The risk score as formulated allows for cases where multiple risks can be scored at a given location. Separate scores should be calculated if separate actions are required to address the different risk. Otherwise, one overall risk score can be calculated if a single project or treatment would address all of the risks.

- Once a set of risk scores have been calculated these can be used as is, or normalized (e.g., divided by the maximum score to obtain normalized scores from 0 to 1).
- Further research would be required to established improved estimates of event likelihood, and the degree to which likelihood may be impacted by climate change, particularly for scour and geohazards.
- Additional research is recommended regarding appropriate values for the adjustment factors for each type of risk. One approach for setting these would be to conduct a revealed preference survey of California residents and/or Caltrans decision makers, in which respondents are asked to prioritize mitigation of different types of risks with similar unadjusted risk scores and mitigation costs. The process could be conducted through a survey, or if with a smaller group, in a workshop setting.

5. Example Calculations Using the Risk Scale

Overview

This section provides example risk score calculations for each of the risk types. The examples are focused on illustrative projects in Districts 1 and 4 with treatments to mitigate (A) Bridge Seismic and Scour Risks, (B) Geohazard Risk, and (C) Sea Level Rise Risk. Table 5 summarizes the parameter values used for all of the examples. The calculations for each example are shown in the following subsections.

Table 5. Default Parameter Values

Parameter	Description	Value	Notes
f_i	adjustment factor for risk *i*	1.000	No adjustment made for risk perception/tolerance
C_p	cost of a property damage crash ($)	9,700	Cal B/C Version 7.2
C_n	cost of an injury accident ($)	148,000	Cal B/C Version 7.2
C_f	cost of a fatal accident ($)	10,800,000	Cal B/C Version 7.2
HC_a	cost per hour, autos ($/hr)	13.65	Cal B/C Version 7.2
HC_t	cost per hour, trucks ($/hr)	31.40	Cal B/C Version 7.2
VC_a	cost per vehicle mile, autos ($/mile)	0.41	Cal B/C Version 7.2
VC_t	cost per vehicle mile, trucks ($/mile)	0.63	Cal B/C Version 7.2

Example A: Bridge Seismic and Scour Mitigation

This example is based on data for Caltrans Bridge 33-0043 on Route 84 over Arroyo de la Laguna in Alameda County. This bridge has seismic and scour needs, and is scheduled for replacement at a cost of $27.2 million. The bridge is illustrated in Figure 11.

Source: Google Maps

Figure 11. Aerial of Bridge 33-0043, Route 84 over Arroyo de la Laguna in Alameda County

Table 6 shows the parameter values required for calculation of seismic risk. As indicated in the table, the bridge carries daily traffic of 13,500 vehicles, approximately 10 percent of which are trucks. Detours around the bridge are approximately 8 miles. The bridge has a seismic score of 0.15. As an older bridge it is at risk of failure in the event of an earthquake, but it is further from an active fault than other higher-risk bridges in the area. In the event of an earthquake that results in bridge failure or closure it is assumed that there is a 50 percent chance of an accident for any cars on the bridge at the time. Probabilities of 30 percent, 15 percent and 5 percent are assumed for property damage, injury and fatal crashes, respectively.

Table 6. Parameter Values for Example A for Seismic Risk

Parameter	Description	Value	Notes
c	seismic calibration factor	0.013	See Section 3
HV_{norm}	normalized product of hazard and vulnerability	0.150	Caltrans 2015 seismic score spreadsheet
MC_1	maintenance cost ($)	100,000	illustrative value
RC_1	reconstruction cost ($)	54,400,000	2 x project cost
ADT	average daily traffic	13,500	2019 NBI data
S	operating speed (mph)	45	posted speed limit

Parameter	Description	Value	Notes
L	road length (miles)	0.059	2019 NBI data
$L_{1,p}$	likelihood of a property damage crash for exposed vehicles	0.30	illustrative value
$L_{1,n}$	likelihood of an injury crash for exposed vehicles	0.15	illustrative value
$L_{1,f}$	likelihood of a fatal crash for exposed vehicles	0.05	illustrative value
ID	incident duration (days)	90	illustrative value
PT	Percent trucks	10	2019 NBI data
DL	detour length (miles)	8	2019 NBI data
DS	detour speed (mph)	30	illustrative value

Table 7 shows the parameter values required for calculation of scour risk. The scour code for the bridge is 3, indicating closure or failure is likely in the event of a 50-year flood. Thus, the annual probability of closure is assumed to be 0.02 (2 percent). Other parameter values are assumed to be the same as those used for seismic risk.

Table 7. Parameter Values for Example A for Scour Risk

Parameter	Description	Value	Notes
Scour critical code	NBI Item 113	3	Results in a value of 0.02 for *P* based on Table 3
MC_2	maintenance cost ($)	100,000	illustrative value
RC_2	reconstruction cost ($)	54,400,000	2 x project cost
ADT	average daily traffic	13,500	2019 NBI data
S	operating speed (mph)	45	posted speed limit
L	road length (miles)	0.059	2019 NBI data
$L_{2,p}$	likelihood of a property damage crash for exposed vehicles	0.30	illustrative value
$L_{2,n}$	likelihood of an injury crash for exposed vehicles	0.15	illustrative value
$L_{2,f}$	likelihood of a fatal crash for exposed vehicles	0.05	illustrative value
ID	incident duration (days)	90	illustrative value
PT	Percent trucks	10	2019 NBI data

Parameter	Description	Value	Notes
DL	detour length (miles)	8	2019 NBI data
DS	detour speed (mph)	30	illustrative value

Table 8 documents the results of the risk calculation based on the above parameters. As shown in the table, closure due to scour is estimated to be 10 times more likely than closure due to seismic risk. The impacts from the two types of risks are assumed to be the same. The overall risk is 1,410,497, which is proportional to the economic loss from seismic and scour risk.

Table 8. Risk Calculation for Example A

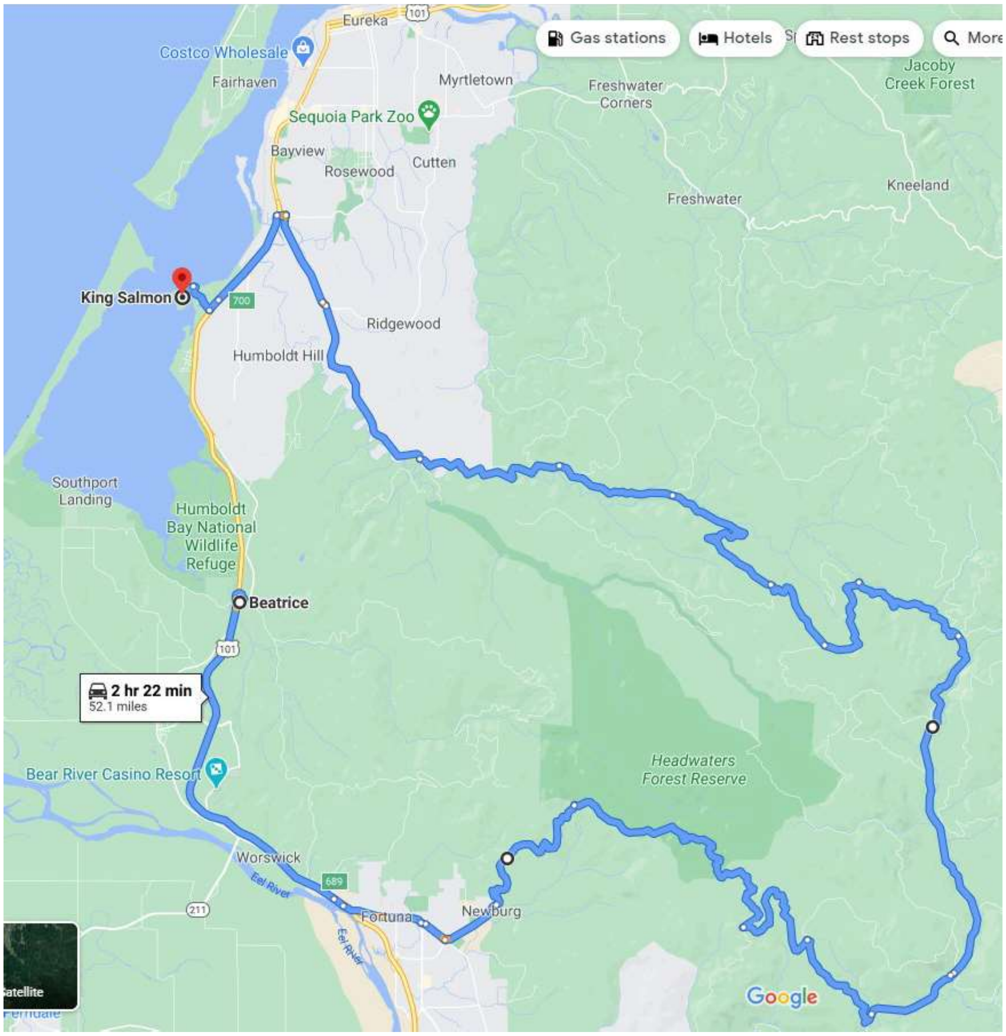
Parameter	Description	Value	Notes
P_1	annual likelihood of seismic hazard	0.002	$c * HV_{norm}$
$I_{1,a}$	agency impact for seismic	54,500,000	$MC_1 + RC_1$
$I_{1,s}$	safety impact for seismic	416,769	See Equation 5
$I_{1,m}$	mobility impact for seismic	9,196,740	See Equation 6
R_1	seismic risk	128,227	$P_1(I_{1,a}+I_{1,s}+I_{1,m})$
P_2	annual likelihood of closure due to scour	0.020	See Table 3
$I_{2,a}$	agency impact for scour	54,500,000	$MC_2 + RC_2$
$I_{2,s}$	safety impact for scour	416,769	See Equation 5
$I_{2,m}$	mobility impact for scour	9,196,740	See Equation 6
R_2	scour risk	1,282,270	$P_2(I_{2,a}+I_{2,s}+I_{2,m})$
R	overall risk	1,410,497	R_1+R_2

Example B: Geohazard Mitigation

This example is based on data for U.S. 101 near Tompkins Hill Road south of Eureka. This section of road is susceptible to landslides. If closed due to a landslide, it would result in detour of over 50 miles. The detour route is shown in blue in Figure 12.

Table 9 shows the parameter values required for calculation of landslide/rockfall risk. As indicated in the table, this portion of U.S. 101 carries daily traffic of 21,800 vehicles, approximately 10 percent of which are trucks. Detours around the area would add approximately 51 miles to a trip. The median landslide susceptibility category for the 0.122-mile section near Tompkins Hill Road is 7. In the event of landslide or rockfall it is assumed that there is a 25 percent chance of an accident for any vehicles on the road at the time.

Probabilities of 15 percent, 8 percent and 2 percent are assumed for property damage, injury and fatal crashes, respectively.



Source: Google Maps

Figure 12. Detour Route from Beatrice to King Salmon

Table 9. Parameter Values for Example B

Parameter	Description	Value	Notes
Landslide susceptibility	landslide susceptibility class	7	Results in a value of 0.02 for *P* based on Table 3
MC_3	maintenance cost ($)	100,000	illustrative value
RC_3	reconstruction cost ($)	2,000,000	illustrative value
ADT	average daily traffic	21,800	Caltrans data

Parameter	Description	Value	Notes
S	operating speed (mph)	55	posted speed limit
L	road length (miles)	0.122	Caltrans data
$L_{3,p}$	likelihood of a property damage crash for exposed vehicles	0.15	illustrative value
$L_{3,n}$	likelihood of an injury crash for exposed vehicles	0.08	illustrative value
$L_{3,f}$	likelihood of a fatal crash for exposed vehicles	0.02	illustrative value
ID	incident duration (days)	2	illustrative value
PT	Percent trucks	10	2019 NBI data
DL	detour length (miles)	51	project team analysis
DS	detour speed (mph)	30	illustrative value

Table 10 documents the results of the risk calculation based on the above parameters. As shown in the table, the largest impact from a landslide or rockfall would be on mobility, as a result of the long detour distance for this location, and given the assumption that a landslide or rockfall would require a combination of maintenance work and additional work to mitigate future risk. The overall risk is 92,560, which is proportional to the economic loss from landslide/rockfall risk.

Table 10. Risk Calculation for Example B

Parameter	Description	Value	Notes
P_3	annual likelihood of closure due to landslides/rockfalls	0.020	See Table 4
$I_{3,a}$	agency impact for landslides/rockfalls	2,100,000	$MC_3 + RC_3$
$I_{3,s}$	safety impact for landslides/rockfalls	424,126	See Equation 5
$I_{3,m}$	mobility impact for landslides/rockfalls	2,103,896	See Equation 6
R	overall risk (landslide/rockfall risk)	92,560	$P_3(I_{3,a}+I_{3,s}+I_{3,m})$

Example C: Sea Level Rise Mitigation

This example is based on data for the Marin County project on U.S. 101 from Seminary Drive to Route 131 listed in *(34)*. This location is susceptible to inundation as a result of sea level rise. The initial estimate for mitigation for this location is $45 million. However, based on discussion with Caltrans, as least initially it is not expected that periodic inundation result in closure and reconstruction of the road. Instead, inundation would result in periodic closures (approximately once per month) and increased maintenance costs.

Table 11 shows the parameter values required for calculation of climate change risk. As indicated in the table, this portion of U.S. 101 carries daily traffic of 136,500 vehicles, approximately 10 percent of which are trucks. Detours around the area would add approximately 0.6 miles to a trip. It is assumed that inundation of the road causes closure approximately 12 days per year (one day per month) and increases maintenance costs by $50,000 per mile. These assumptions are based on the analysis performed for State Route 37, which is already subject to inundation *(40)*. No safety risk is modeled in this case, as it is assumed that the road would be closed prior to inundation. An annual maintenance cost of

Table 11. Parameter Values for Example C

Parameter	Description	Value	Notes
r	discount rate	0.04	Cal B/C Version 7.2
n	years until inundation is projected to occur	31	Caltrans data
MC_4	maintenance cost ($)	35,000	$50,000 per mile based on Route 37 analysis
RC_4	reconstruction cost ($)	0	Inundation assumed to cause periodic closure and increased maintenance but not reconstruction
ADT	average daily traffic	136,500	Caltrans data
S	operating speed (mph)	55	posted speed limit
L	road length (miles)	0.70	Caltrans data
$L_{4,p}$	likelihood of a property damage crash for exposed vehicles	0.00	assumed that road will be closed prior to inundation
$L_{4,n}$	likelihood of an injury crash for exposed vehicles	0.00	assumed that road will be closed prior to inundation
$L_{4,f}$	likelihood of a fatal crash for exposed vehicles	0.00	assumed that road will be closed prior to inundation
ID	incident duration (days)	12	monthly closures assumed

Parameter	Description	Value	Notes
PT	percent trucks	10	2019 NBI data
DL	detour length (miles)	0.6	project team analysis
DS	detour speed (mph)	30	illustrative value

Note the probability of inundation is approximated for this example based on the discount rate (r) and estimated number of years until inundation occurs (n). Based on these parameters the discounted probability is calculated as:

$$P = \frac{1}{(1 + 0.04)^{31}} = 0.30$$

Table 12 documents the results of the risk calculation based on the above parameters. As shown in the table, it is assumed that inundation of the road would result in a one-year closure costing travelers $28,284,233 in detour costs. The overall risk is 21,725,863, which reflects the reconstruction cost and detour cost discounted for the fact that inundation is not predicted to occur until approximately 30 years in the future.

Table 12. Risk Calculation for Example C

Parameter	Description	Value	Notes
P_4	discounted likelihood of closure	0.30	See discussion in Section 3
$I_{4,a}$	agency impact for climate change	35,000	$MC_4 + RC_4$
$I_{4,s}$	safety impact for climate change	0	See Equation 5
$I_{4,m}$	mobility impact for climate change	929,893	See Equation 6
R	overall risk (climate change risk)	286,052	$P_4(I_{4,a}+I_{4,s}+I_{4,m})$

Discussion

The examples illustrate that it is feasible to calculate a risk score using the recommended approach and available data. The risk scores vary considerably between the examples, from 92,560 for landslide/rockfall risk to 1,410,497 for the combination of seismic and scour risk. In interpreting the scores, it is important to note that the score should be divided by mitigation cost to support prioritization, and the range in mitigation costs is also large: from $2 million for landslide/rockfall risk to $27 million for seismic and scour risk to $45 million for climate change risk.

6. Implementation of the Risk Scale

Overview

This section discusses considerations related to implementation of the recommended risk scoring approach. The following sections discuss potential applications of the risk score, recommended thresholds for summarizing risk by probability and consequence, data requirements for calculating risk scores and the challenges and opportunities for future improvement.

Potential Applications

Once calculated, the risk scores can be used to support a variety of applications. Potential applications and considerations related to each include the following:

- **Identifying risks of a given type:** one can use the risk scores and score/cost ratios to compare risks of a given type – seismic, scour, landslide or seawater inundation. In each case the risk score provides an indication of the magnitude of the risk, while the score cost ratio scales the risk by the mitigation cost. Generally, the score/cost ratio provides the most meaningful metric for comparing risks at different locations. However, calculating this measure requires knowledge of the mitigation cost. If the mitigation cost is unknown or expected to be similar between a set of locations, then it may be more useful to compare risk scores rather than score/cost ratios.

  An important consideration in comparing risks between locations – particularly inundation risk – is the timing of the risk. Scour, landslide and seawater inundation risk are all expected to increase in the future. The risk score provides a point estimate of the risk, but it may be important to consider how risk is changing over time. This is particularly important in the case of seawater inundation, which is occurring in some locations already, but not expected to occur in other locations for some time. The risk scoring approach accounts for when inundation is expected to occur, discounting future risk. However, for many applications it may be preferable to either screen out risks that are expected to be realized until a future time – or, alternatively, focus specifically on these risks to support planning efforts.

- **Comparing locations considering multiple types of risks:** the risk scores are intended to facilitate comparison of different locations considering the range of different risks at each location. In this case, an overall risk score and overall score cost ratio can be calculated considering all four risk types. The examples in Section 5 an in the appendix show how different risks can be combined. However, as a practical matter it may be necessary to further weight the different types of risk to account for risk perceptions.
- **Prioritizing investments:** the risk score can be added as a factor in prioritizing projects. The score is constructed such that it represents the approximate annual savings to Caltrans and road users from mitigating the four types of risks addressed. An important consideration in project prioritization is the programming period – how frequently are programming decisions made? Ideally the prioritization process should incorporate this interval explicitly. For instance, one might assume that if projects are programmed every two years, the benefit associated with a project could be approximate by calculating total benefits realized over a two-year period.

Risk Thresholds

For the purpose of summarizing risk is frequently useful to create bins to classify risk by probability and impact (consequence). An initial set of thresholds have been developed based on the analysis described in Appendix A. The basic approach to establishing these thresholds was as follows:

First, thresholds for five categories of probability were defined based on the range in the data, in turn defined based on how various input variables are used to estimate probability. These are summarized in Table 13. The table lists five categories, the probability range for each category, and the corresponding values that result in this range for each risk type. The probabilities are expressed as a return period: the time until the risk is expected to occur. For sea level rise the years to inundation is used for this. For the other risk types the inverse of the probability is used. Where a location is subject to multiple risks, the minimum is used.

Table 13. Recommended Probability Categories

Category	Return Period (years) >	Return Period (years) ≤
1	500	N/A
2	250	500
3	25	250
4	10	25
5	N/A	≤10

Second, the results described in Appendix A were reviewed to determine what variables are most correlated with the risk score ratio. The risk scoring approach described in Section 4 includes a number of different variables, but as a practical matter, the consequences are largely driven by a small number of variables, at least in the test data set. We found that the overall risk cost ratio, *RCR*, is proportional to the product of probability, traffic, and detour length:

$$RCR \approx P * ADT * DL \; (7)$$

Based on this relationship, it was determined that the consequence term should be calculated as *f* **ADT* * *DL* where *f* is a weighting factor set to 1 by default. With this approach, the product of probability and consequence approximates the overall risk score ratio. The consequence value can be scaled as needed by adjusting *f,* such as to account for perceptions of different types of risks or changes in the duration of risk consequences relative to the defaults used here. Note that the consequence term can be further refined by introducing additional variables. This can improve the correlation with risk cost ratio, but at the expense of complicating the interpretation of the results.

The next step was to define ranges for the consequence categories. These ranges were defined based on the range in the data for Districts 1 and 4, with the ranges adjusted to obtain a reasonable distribution of values between the different categories. The resulting consequence categories are summarized in Table 14.

Table 14. Recommended Consequence Categories

Category	*f*ADT*DL ≥*	*f*ADT*DL <*
1	0	20,000
2	20,000	100,000
3	100,000	500,000
4	500,000	1,000,000
5	1,000,000	N/A

Note: consequence is approximated by multiplying an adjustment factor (1 by default) by daily traffic (vehicles/day) and detour length (miles)

Table 15 below shows the distribution of risks by probability and consequence categories for the District 1 and 4 data analyzed as described in Appendix A. Note this analysis includes all of the highway segments and bridges in these districts with some level of risk, not only the highest risk locations. Table 16 shows the average risk/score ratio calculated for each category. The ranges are shaded such that the category with the highest ratio is in red, and the lowest is in green.

Table 15. Percentage of Locations by Risk Category, Districts 1 and 4

	Probability				
Consequence		**2**	**3**	**4**	**5**
1	6.71%	2.83%	4.06%	0.04%	1.89%
		4.08%	6.36%	0.12%	3.56%
		4.79%	7.89%	0.39%	3.99%
		1.95%	2.76%	0.38%	1.68%
		1.35%	2.35%	0.36%	0.78%

Table 16. Average Risk Score Ratio by Risk Category, Districts 1 and 4

	Probability				
Consequence	**1**	**2**	**3**	**4**	**5**
1	0.01	0.01	0.07	0.01	1.68
2	0.01	0.01	0.09	0.13	1.88
3	0.02	0.05	0.36	2.37	6.18
4	0.06	0.12	1.30	5.14	12.76
5	0.17	0.26	3.73	6.69	29.99

Note that the risk categories presented here are intended to help communicate the general level of severity of different risks and/or as an initial screening tool. We do not recommend using the categories as an alternative to calculating a risk score in cases where sufficient data are available to calculate a score.

Data Requirements

To a first approximation, Caltrans has demonstrated, through compiling data for Districts 1 and 4, that much of the data required for calculation of a statewide risk score is already available. Data required for the calculation include the following:

- Road inventory detailing ADT, truck percent, length and number of lanes by road segment
- Bridge inventory including ADT, truck percent, length, width and scour critical code (NBI Item 113)
- Normalized seismic hazard * vulnerability score for each bridge
- Landslide susceptibility by road segment
- Expected years until seawater inundation occurs by road segment
- Detour length and speed for each road segment and bridge
- Treatment costs by location and risk

Of the data listed above, all are readily available with the exception of the last two on the list: detour data and treatment costs. Detour length is available for each bridge, but has not been computed for each road segment. For the analysis described in Appendix A the detour length of each road segment was estimated using the detour length for the nearest bridge, and the detour speed was assumed to be 30 mph. Regarding treatment costs, representative unit costs were assumed for the analysis described in the appendix.

Challenges and Opportunities for Improvement

While the data are generally available for supporting the risk scale, there some fundamental challenges in developing any risk score, and further challenges in each of the area. This section describes the various challenges in calculating and implementing the risk score described here, and opportunities for improving the approach. The basic challenges include the following:

- **Finding the appropriate balance** between an approach that is technically accurate but requires more data and one that is less accurate but is easier to implement and relies on readily available data. To address this challenge, a systematic process can be implemented to use simple methods and less data to inform the initial district or state-wide prioritization and then transitions to a process that relies on more data for only the high risk areas, where the improved risk accuracy is useful in decision making. The subsections below discuss where additional data, if available, can be used to develop an improved scoring approach.
- **Addressing the scenarios or design events to use**. Ideally the scoring methodology would account for any and all risk in each area being addressed. In practice, it is impractical to analyze every possible scenario (e.g., an earthquake of any magnitude

or flood of any size) and estimates of likelihood and consequence are made for specific scenarios or events, or defined range of outcomes. Defining such scenarios provides a means for specifying Caltrans' risk tolerance – as risks below some threshold level of likelihood or tolerance would be screened out if the analysis is restricted to risks meeting specified criteria.

- **Establishing assumptions regarding the effect of various treatments**. The risk scoring approach developed through this effort is intended to support prioritizing investments. Thus, ideally scores should reflect the degree to which a proposed investment will reduce risk rather than the overall risk at a given physical location. We have assumed that a treatment will mitigate all of the risk of a given type. Further work is needed to better define the treatments that may be considered and their likely impact on risk.
- **Responding in temporal changes to risk.** The level of risk across the Caltrans system will vary in response to changes that influence likelihood or consequence parameters. For instance, a wildfire will increase stormwater runoff, resulting in increased likelihood for sour and landslides. Similarly, changes in ADT or truck percent, while typically gradual, can influence the consequence inputs into risk. Having a systematic screening approach for rapidly evaluating changes in risk following events such as wildfire can be useful for communicating where measurable increases in risk exist and implementing proactive mitigation.

The approach presented in Section 4 is intended to address the above challenges as well as possible given readily available data. However, even with the recommended approach there are key parameters that may merit further analysis to better quantify. Also, it may be desirable to improve the quality and/or level of detail in the data at a later time. The following subsections further detail the issues and opportunities for improvement by risk type.

Seismic Vulnerability

Much of the data required for assessing seismic vulnerability has already been compiled. Additional desired includes:

- Better relating the hazard and vulnerability scores to the likelihood of bridge closure. As discussed in Section 3, as an initial assumption we have set the scaling factor *c* equal to 1/75. Further research would be needed to better establish this factor, and better determine the extent to which the *HV* values calculated by Caltrans approximate seismic risk;
- Likelihood of property damage crashes, injuries, and fatalities; and

- Assumptions regarding how the seismic score may change as a result of performing a seismic retrofit. We have assumed that seismic risk is mitigated by any treatment.

Scour Vulnerability

Data required for assessing scour vulnerability that has been compiled includes the NBI data for each bridge. Additional desired data includes:

- Assumptions regarding the risk of failure for scour critical bridges;
- Likelihood of property damage crashes, injuries, and fatalities; and
- Guidance or assumptions regarding how to quantify scour risk for bridges not classified as scour critical in the NBI.

The approach presented in Section 3 yields a risk score for scour utilizing available data. However, ideally there would be better data available to allow for a more accurate assessment of scour risk. NBI Item 113 provides little quantification of the likelihood of damage or bridge failure as a result of scour. Further discussion is needed of the events or scenarios that should be addressed for this area, and the approach for estimating event likelihood given the available data.

An additional challenge is that NBI Item 113 provides no real quantification of how prone to scour a given bridge is – only whether or not a bridge is "scour critical." Ideally in the future it would be possible to supplement this item with additional detail to better distinguish between bridges that are scour critical but have different degrees of exposure to scour. Conceptually, this process would first be performed at a District or corridor scale screening level using correlations with factors that quantify scour potential. For instance, an office or desk-top based effort to measure factors such as channel slope above and below the crossing, angle of channel intersection with the structure, geology, and basin runoff coefficients could be inputs into an algorithm that informs estimated scour likelihood ranges.

Landslide and Rockfall Vulnerability

Data required for assessing landslide/rockfall vulnerability includes the California Geological Survey statewide landslide susceptibility mapping. A challenge for this area is that key model parameters have been estimated based on expert judgement, but ideally these would be informed by further analysis of historic data. These include:

- Risk of closure based on the landslide susceptibility class, hazard location relative to the roadway, and slope hazard type;
- Average duration of closure;
- Agency mitigation costs;
- Likelihood of property damage crashes, injuries, and fatalities; and

- Reduced risk as a result of treatments.

Another challenge with the current approach is that only one aspect of slope instabilities (deep seated landslides) is highlighted and the other slope hazards are not available in a comparable geospatial database that is intersected with the Caltrans network. The deep-seated slope instability type often originates beyond the right-of-way and may impact the travel lanes differently and with less frequency than the other types of slope instabilities, such as rockfall from Caltrans owned cut slopes. Relying on only one instability type primarily located on slopes beyond Caltrans' right of way as a surrogate for all slope instability types may not accurately reflect the performance of the asset.

Incorporating geospatial information to screen for credible landslide and rockfall hazards in the approach for calculating the risk score would reduce uncertainty and provide for a more accurate assessment of the risk. This screening could include factors such as slope angles above and below the roadway within a certain width, proximity of steep slopes (e.g., credible rockfall) to the roadway, presence of tall embankments above sloping natural ground, and aspect.

Climate Change Vulnerability

Regarding climate change vulnerability, it is important to note that this area addresses a number of different risks, all of which are made more likely as a result of climate change. The approach defined in Section 3 specifically models risk of inundation from sea level rise and storm surge, while allowing for revisions to other risk probabilities as a result of climate change. Given this approach, the critical data required for assessing climate change risk is the number of years until inundation is predicted for each road segment.

One challenge in this area is that key model parameters have been illustrated in the examples, but further analysis is required to quantify them more precisely for a given location, particularly the average duration of closure and mitigation cost. Another challenge regarding this area include accounting for the fact that severity of inundation will likely change over time, with the frequency of inundation gradually increasing for roads that are subject to periodic inundation. Also, an approach has not been defined for adjusting risk for scour and landslides/rockfalls to account for climate change impacts.

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Appendix A. Risk Score Calculations for Districts 1 and 4

Overview

This appendix describes a test of the risk scoring approach performed using data for Districts 1 and 4. Data for the test were obtained for Caltrans. The project team developed a proof-of-concept Microsoft Excel spreadsheet illustrating calculation of a risk score considering scour, seismic, landslide and sea level risk. The spreadsheet is titled "risk_calc_20210423.xlsx." The following subsections documents the analysis spreadsheet components and

Spreadsheet Components

The proof-of concept spreadsheet shows the calculation of the proposed risk score for highways and bridges in Caltrans Districts 1 and 4. The Form sheet of the spreadsheet details the calculation for a specific highway section and/or bridge. To use this sheet ,one must enter a highway segment ID and/or bridge ID in the yellow-shaded cells at the top of the sheet. A list of highway sections and bridges is shown at the bottom of the sheet. The resulting risk score is shown in Cell B13, as depicted in Figure A-1 below.

Caltrans Risk Score
Example Calculation - Form View

Instructions: Enter a Highway Segment ID and/or Bridge ID. The risk score and score/cost ratio is shown at the bottom of the form.

Location

Description	Value	Description
Highway Segment ID	1966	*Route: 001, From: 12.515, To: 15.3, County: SON*
Bridge ID	20 0070	*Feat Intersected: RUSSIAN GULCH, Facility Carried: STATE ROUTE 1, County: SONOMA, Milepost: 15.224*

Enter Highway Segment ID and/or Bridge ID

Results

Description	Value
Risk Score	1,445,792
Mitigation Cost	39,637,400
Score Cost Ratio	0.04

Risk score, cost and score/cost ratio

Location-Derived Parameters

	Value	
Description	Pavement	Bridge
Segment length (miles)	2.785	0.020
Pavement area (lane miles)	5.570	N/A
Bridge area (square ft)	N/A	3,237
ADT	3,720	2,225
Average speed (mph)	40	50
Percent trucks	5	0
Detour length (miles)	28	28
Detour speed (mph)	30	30
Seismic score	0.00	0.00
Scour critical code	-1	8
Landslide susceptibility class	7	-1
Years until inundation	0	-1

Figure A-1. Risk Score Proof-of-Concept Spreadsheet

The Table sheet of the spreadsheet reproduces the same calculations as the Form sheet, but here calculations are made for each row of the spreadsheet. The sheet has one row for each highway segment and bridge ID in Districts 1 and 4, filtering out those with a score of 0. In cases where a bridge lies along the highway segment both a highway segment ID and bridge ID are entered on the row.

Two additional sheets detail the parameters used for the calculations. The Constant Parameters sheet has parameter values used for each highway and bridge. The Lookup Parameters sheet has parameters looked up by highway or bridge, such as average daily traffic (ADT), segment length, etc. Please note the following regarding the parameters:

- Parameter values have been established for illustrative purposes as discussed in the interim report on the project. Further review is required to finalize parameter values.
- The results are highly sensitive to agency cost assumptions. Here, agency impact is assumed to be $200/square feet of bridge deck area for seismic and scour, $2 million per road mile for landslides, and $50,000 per road mile for inundation. The mitigation cost has been assumed to be the same as the agency impact for seismic, scour, and landslides, and $6 million per lane mile for inundation. Thus, there is no penalty function applied in estimating agency impact for seismic, scour and landslides. For inundation we have estimated agency impact as the increased maintenance cost of a road that is periodically inundated but not reconstructed based on the data Route 37 in Marin County (*40*). The reconstruction cost is based on Caltrans estimates for selected potential projects (*34*).
- Detour distance is quantified by bridge, but not by highway segment. To obtain an initial value for this parameter for each highway segment we have used the detour distance for the nearest bridge on the same route and in the same county, flagging cases where this value may be misleading. Even if bridge lies along a given highway segment the bridge detour distance may be different from the detour distance for the highway segment.
- Weights have not been set for the different risk types, but would presumably be established prior to using the risk scores.

The Graphs sheet has results for the individual risk components: scour, seismic, landslide and sea level rise (inundation) risk scores. The results have been further filtered on this sheet to show only highest risk locations. Risks included in the graphs are:

- All seismic risks
- Scour risk where the likelihood is 1% or greater (scour code of 0, 1, 2, 3, 6 or 7)
- Landslide risk where the likelihood is 1% or greater (class of 6 or greater)

- Sea level rise risk where the years to inundation is 0

Note the values in this sheet are static and do not change based on changes in the parameter values.

Analysis Results

The spreadsheet illustrates that it is feasible to calculate risk scores for highways and bridges in Districts 1 and 4 using the available data, with the major qualifications that the parameter values used for the calculations – particularly the cost assumptions and detour distances for highways – require further review.

Figure A-2 shows the risk scores calculated for each risk type. This graph shows scores on the horizontal axis and cost on the vertical axis. Both axes are plotted on a logarithmic scale. The figure illustrates that the most prevalent type of risk is landslide risks. Bridges risks (seismic and scour) tend to have the greatest cost. By contrast, landslide and inundation risks typically have higher scores, and in many cases are less costly to mitigate than bridge risks. However, the cost figures for these risks may be misleading in cases where one project would be required to address the risk of multiple highway segments. Ideally risk locations should be group to represent the set of segments that would realistically need to be addressed to fully mitigate the risk at a location.

Figure A-3 shows the distribution of the score cost ratios for each type of risk. For each type of risks it shows the percentage of locations with different risk scores. The risk score bins are scaled logarithmically. It illustrates that inundation risks tend to have the greatest score cost-ratios, while the other risk types are distributed similarly to each other.

Note the following revisions have been made to the spreadsheet based on Caltrans' review of the intial results provided previously:

- The results have been filtered to include only the locations with the highest risk, as described above.
- The treatment of sea level rise risk has been adjusted. Previously we assumed that when inundation occurs the road is closed for one year and the road must be reconstructed. Caltrans staff observed that this assumption is not valid for the many roads already classified as inundated. At least at present inundation is a recurring event that does not trigger permanent closure and reconstruction of the road. Thus, in the revised figures, inundation is assumed to cause closure of the road approximately once per month, as well as increased maintenance costs.
- Agency costs of inundation have been adjusted based on further analysis of Caltrans data, as discussed above.

Figure A-2. Risk Score by Type of Risk and Cost

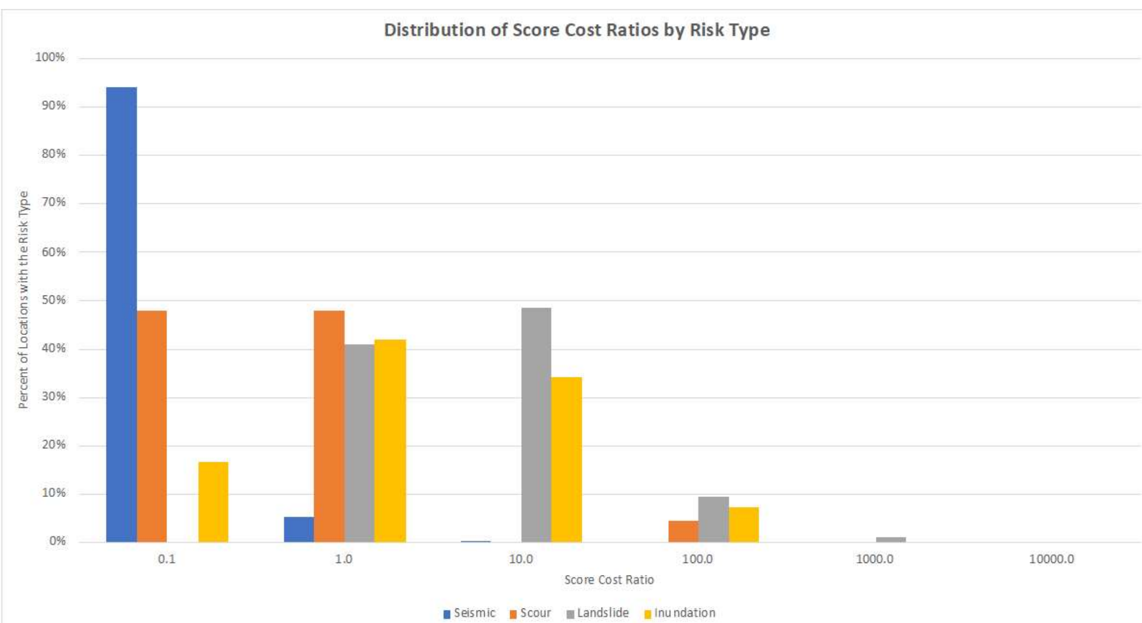

Figure A-3. Distribution of Score Cost Ratios by Type of Risk

Appendix B. Peer Review

Attached is a peer review memorandum prepared by Mr. Gordon Proctor. The review was performed as part of the project at Caltrans' request. Note the peer review was performed based on an initial version of the risk score report. The draft report was subsequently revised to help incorporate the comments from the review.

Memorandum

To: William Robert, Spy Pond Partners
From: Gordon Proctor, Proctor Associates.
Re: Review of Caltrans Statewide Risk Assessment Scale draft report
Date: Feb. 15, 2021

I offer the following comments after review of the above-mentioned report. These are not necessarily in order of importance.

The logic and process proposed by the study are sound and consistent with similar processes found in the literature reviews conducted for research for the Federal Highway Administration (FHWA) and the National Cooperative Highway Research Program (NCHRP). The topic you are studying is relatively new and there are not many relevant examples. However, the approach you propose is consistent with the studies done by the departments of transportation in Utah and Colorado. Also, you build from established frameworks such as ones for rockfall programs or seismic retrofit programs.

The study builds upon accepted practices such as:

- Using readily available threat data such National Bridge Inventory (NBI) scour data, state geologic data, and publicly available climate data.
- It also comports with the state of the practice by using data such as vehicle operating costs, crash cost data, and length of detours to calculate user costs or impacts.
- The study is consistent with good practice by using available data to allow rapid analysis of sites while avoiding the time and expense of acquiring proprietary or hard-to-acquire data.

A particular value of the study is to provide a means to compare disparate threats by the common denominator of the cost of the threat discounted by the probability of the threat occurring. This type of analysis meets the apparent intent of the study which is inferred to be seeking a means to compare disparate threats by the common denominator of their cost to mitigate. The suggested approach of the study fulfills that objective. As an editorial note, perhaps re-emphasizing the scope or intent of the study could be helpful to the reader.

A question that arose regarding the risk already assumed for rockfall, rockslides, and landslides. Do the Caltrans assessments of those sites include data on the setback of the toe of the slope to the edge of pavement? If so, that would be a risk factor. The more the setback, or the presence of catchment mitigation, the less risk to the motorists. The report did not note whether that was a factor which already is incorporated into the Caltrans assessments of sites.

Because the logic of the study was sound, my thoughts quickly shifted to implementation issues. Or, what issues may arise once this process is applied statewide to Caltrans assets.

First, will the total cost of the assessed risk lead to an investment fund to “buy down” the risks? For example, once the total risk values are assessed, will Caltrans set aside funding to mitigate the highest-ranked sites? If so, another complex problem arises. That is how to equate the benefit of buying down these threats compared to ensuring the condition of assets? There is no easy answer to that question and it probably will come down to a policy decision if it is a “zero sum” tradeoff.

Second, a “no regrets” risk-mitigation strategy could be to develop for the highest-ranked sites threat-response plans should the sites fail before they are mitigated. These plans could be particularly valuable when a site faces multiple threats but may not be mitigated for many years. Having a ready plan to post detours or have contracting methods in place for rapid remediation could lower the user costs of detours. These plans can be relatively inexpensive. If they reduce the mobilization time for a response, the reduction in user costs caused by detours can fall, giving the plans a positive benefit-cost-ratio.

Balancing the decisions of when to mitigate sea-level-threatened sites could be influenced by factors such as maintenance costs and right-of-way expenses. The study does not now include maintenance costs for sea level rise. However, it is likely that sea level impacts will be gradual with periods of inundation during storms or king tides. Those events will bring maintenance costs. In such cases, the avoidance of maintenance costs could be a factor in calculating the benefit/cost of permanent mitigation and justify expediting the project. On the other hand, the site on 101 in Marin County probably is presently complicated by very expensive right-of-way. Over time, the businesses along that section are likely to move as sea level rise makes their location impractical. Delaying the urban sections could allow the businesses to amortize their investments before their properties are taken, and reduce the State’s right-of-way costs.

A third practical implication is the need to rank all the sea level sites by their date of inundation. This probably was intended in later stages of the analysis. Knowing the timing of the threatened sites would allow for sequencing of the mitigation. The plan-development process is likely to be complex and time consuming. By their very nature, coastal sites are environmentally and culturally sensitive. Knowing how many sites per decade should be mitigated would allow for a multi-decade program to address them. Such a program could be even larger than Caltrans’ historic efforts to seismically retrofit bridges. Such a program probably will require dedicated funding and complex project-development and public involvement efforts. The plan-development timelines for slope failures or bridge replacements are likely to be shorter than for coastal mitigation. Thus, the time factor for coastal mitigation can be important.

A fourth practical implication is that specialty staff probably will want to see the rank order of sites by risk area. The geotech staff will want to see the rockfall and landslide sites in rank order, as will the structures staff want to see the scour-and-seismically threatened sites in rank order. As much as agencies try to not be influenced by the “color of money” funds do come in categories. The program mangers of those categories will want to see how these threats may influence their multi-year programs. Some mitigation may be less expensive if incorporated into on-going maintenance and preservation activities.