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A Practical Framework to Assess the Sustainability and Resiliency of Civil Infrastructure

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A Practical Risk-Based, Probabilistic Framework for Unifying Sustainability and Resiliency Assessments of Civil Infrastructure

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Abstract

Research within civil engineering is focusing on newer ideas and philosophies such as sustainability and resiliency (S&R). This is evident in the development of frameworks to assess sustainability or the resiliency of civil infrastructure. Several frameworks were developed by researchers to quantify sustainability and resiliency of civil infrastructure. It is evident that the sustainability and resiliency are not mutually exclusive and is important to asses these aspects at the same time and frameworks be able to accommodate simultaneous assessments. While there are other frameworks that follow a unified approach to S&R assessments, they do not account for the risk of the hazard as a part of the framework. In the proposed framework, an attempt was made to include the risk of the hazard as a part of the assessment to gain a realistic perspective of the hazard impact. This paper presents explicit steps to use the framework, along with an example of using the frame work in assessing an earthen dam subjected to two types of hazards, earthquakes and floods. Novel aspects of this framework revolve around the simplicity, and flexibility of the framework. Major input parameters are user-defined, which allows for a wide range of variable to be considered when determining the overall quality of the infrastructure.

Keywords chosen from ICE Publishing list: earth dams, sustainability, statistical analysis, infrastructure planning

List of ACRONYMS and Units

ASCE	*American Society of Civil Engineers*
bhp	*Break Horsepower*
BSU	*Boise State University*
DPSIR	*Driver, Pressure, State, Impact, Response*
EC	*Embodied Carbon*
EE	*Embodied Energy*
EPA	*Environmental Protection Agency*
FEMA	*Federal Emergency Management Agency*
FS	*Factor of Safety*
g	*Grams*
hp	*Horsepower*
ICE	*Institution of Civil Engineers*
K	*Hydraulic Conductivity*
lbs.	*Pounds*
kN.	*Kilonewtons*
LCA	*Life Cycle Analysis*
LCCA	*Life Cycle Cost Analysis*
LEED	*Leadership in Energy and Environmental Design*
PHA	*Peak Horizontal Acceleration*
S&R	*Sustainability and Resiliency*
USACE	*United States Army Corps of Engineers*
USGBC	*United States Green Building Council*
USGS	*United States Geological Survey*

1. Introduction

Numerous cities, agencies, firms, and universities are focused on developing infrastructure that is both sustainable and resilient. In order to measure the current condition of a structure, assessment methods that determine the functionality of a system must be used. Assessment methods typically consist of measuring key metrics that directly relate to the sustainability and resiliency of the entire system. Methods on how to measure these metrics are then formatted into a framework which may aid researchers and practitioners in computationally performing an assessment. Several attempts have been made to develop a framework which separately assess the sustainability or resiliency of infrastructure. However, balancing the needs to build robust, and resilient infrastructure with the focus on sustainable development requires a probabilistic approach that accounts for both the likelihood of an extreme event and its consequences while ensuring that the economic, environment, and the societal impacts are minimized. The current frameworks that attempt to develop a unified approach to assessing sustainability and resiliency lack robustness and simplicity sufficient enough to employ the framework beyond a collegiate setting.

In an effort to make a framework capable of assessing the Sustainability and Resiliency (S&R) of civil infrastructure that accounts for the risk of a catastrophic event, this paper proposes a simple, yet robust framework that is intended to be used by decision making agencies or engineering firms. Computations are performed in a common platform, which is readily accessible by engineering firms, and results are reported in an easy to use, graphical format which is representative of the overall quality of the system. An example of how to perform this assessment is provided to show how the framework may be applied to civil infrastructure. The goal was to develop a framework that allows practitioners to assess the overall quality of their design from an S&R perspective, which will inevitably lead to a more resilient, and sustainable built environment.

2. Background

The term sustainable development originated from the Brundtland Commission in 1987, under the direction of the United Nations. The Brundtland Commission defined sustainable development as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs.” (United Nations World Commission on Environment and Development, 1987). To further this concept, the American Society of Civil Engineers (ASCE) has defined sustainable development as “a set of environmental, economic, and social conditions [the “Triple Bottom Line” (Elkington, 1997)] in which all of society has the capacity and opportunity to maintain and improve its quality of life indefinitely, without degrading the quantity, quality, or the availability of natural, economic, and social resources” (American Society of Civil Engineers, 2017). For the purpose of this paper, the definition of sustainability closely follows that of ASCE’s Triple Bottom Line approach. The measure of quality can be assessed using a balanced approach between environmental, social, and economic impacts. Each component of the Triple Bottom Line is considered a pillar which is used to balance the quality of the system. The more the system reaches an equilibrium among all pillars, the higher the overall quality of the system, as shown in Figure 1.

The term resiliency has been used in a wide range of disciplines and applications, with some that focus on psychology or biology, and some focus on mathematics and engineering. For the purpose of this paper, the term resiliency is defined as the measure of a system’s ability to withstand an impact from a low probable high consequence event. High consequence events could be anything that may cause failure in the system, such as earthquakes, hurricanes, floods, of fire. Quantification of a system’s ability to withstand catastrophic impact can be highly detailed, and complex, leading to research in resiliency.

Work performed by Bocchini et al. (2014) outlined a resiliency quantification method, which included four pillars of resiliency as, Robustness, Resourcefulness, Rapidity, and Redundancy. Each pillar measures certain metrics associated with the infrastructure, which determine the ability of a system to rebound after the occurrence of a catastrophic event. Robustness is the measure of a system’s overall strength, or ability to withstand the impact of a catastrophic event. Resourcefulness is defined as the ability and willingness of the project personnel to identify, obtain, and use material and/or other assets to perform the rehabilitation efforts after an event. Rapidity is the ability to reinstate functionality in a timely manner by minimizing losses and avoiding interruptions. Redundancy accounts for the extent to which a system or its components are substitutable and can accommodate an unrestricted functionality after an event. In addition to the four Rs, a resilient infrastructure should also be cognizant of and work towards minimizing its impact on adjacent facilities.

2.1 Sustainability Frameworks

Methods to measure the sustainability of a system have been created since the 1987 Brundtland Commission. In this time, a wide range of methods have been proposed, all of which follow the guidelines of sustainable development outlined by the Brundtland Commission. Sustainability frameworks are numerous and can range from focusing on one aspect of the system such as the environmental impacts or the total cost of the infrastructure, to more holistic approaches which quantifies all three pillars within the Triple Bottom Line. Although many assessment frameworks exist, only a few of them are described here.

2.1.1 Life Cycle Analysis

One of the most widely accepted frameworks used to assess the sustainability of a system or infrastructure is the Life Cycle Analysis, (LCA). The LCA identifies and measures the overall impacts throughout the life span of the system. Impacts, or metrics that are measured could include environmental impacts due to the extraction and production of materials, construction, vehicle use, operation and maintenance, demolition or rehabilitation at the end of the life cycle as well as disassembly and re-purposing. Several frameworks exist to compute the LCA of a system, one of which is provided by Eckelman et al., (2014) to show an example of how to compute the LCA for a given system. This example used environmental and economic assessment methods specific to a water storage facility. Further, the example provided by Eckelman et al., (2014) was to show how the LCA method can analyse any type of infrastructure, using pre-determined weighted input values specific to the project goals. Each factor is measured and related in a cost/benefit analysis, then weighed against competing alternatives. A benefit and drawback to using the LCA is that it is user dependent, and output is strictly dependent upon the input. This dependency requires users to have explicit knowledge of each design alternative, as well as every input factor and the associated weights.

2.1.2 Emission Factors

Measuring civil infrastructure's level of environmental impact has been researched by several agencies, such as the United State Environmental Protection Agency (EPA), and Circular Ecology (Circular Ecology, 2016; US Environmental Protection Agency, 2017). The EPA has developed emission factors specific to sources such as vehicles, or processes that emit pollutants into the atmosphere. The EPA focus on six criteria pollutants, Particulate Matter, Nitrogen Dioxide, Carbon Monoxide, Sulphur Dioxide, (PM2.5/PM10, NOX, CO, SO2), Ozone, carcinogenic and non-carcinogenic toxic air pollutant, and hazardous air pollutants for each project, or process (EPA, 2014; Office of Transportation and Air Quality US EPA, 2008). Inclusion of these emissions may be performed in conjunction with the LCA or other assessment methods. Since emissions are only generated due to material usage or consumption, they act as a key component to determine the energy, carbon output, global warming potential, or fuel consumption of a project. Generally speaking, emissions are determined based on fuel consumption from construction or operational activity. A key aspect of measuring emissions is that the amount, and type of emissions will vary as the fuel type and machine efficiency vary.

2.1.3 Infrastructure Specific Frameworks

The United States Green Building Council (USGBC) was formed in 1993, which developed a framework called Leadership in Energy and Environmental Design (LEED). The primary focus of LEED is on buildings, material use, water use, and community development. LEED is a sustainability framework developed to measure what impacts a structural development may have on the environment (U.S. Green Building Council, 2018). As reported by the USGBC, the LEED framework assists developers in making construction choices to reduce waste generation, water use, and energy consumption. The benefits of constructing with this environmental focus increases the economic worth, human health, and adds value to tenants, while decreasing operational costs, energy consumption and waste generation. Because LEED encompasses the social and economic impacts through focus on a reduction in environmental impacts, they can market this framework and rating system under the same definition of sustainability as ASCE's Triple Bottom Line approach.

Another rating system similar to LEED is Greenroads. Greenroads similarly follows the Triple Bottom Line approach because it encompasses the environmental, social, and economic impacts of a project, however this system is specific to transportation systems (Muench et al., 2011). Quantification of sustainability is outlined by Greenroads as defining features, methods and measurement of specific goals of the project, as well as encouraging new practices and promoting incentives for sustainable development (Muench et al., 2011).

Misra and Basu (2011) developed an assessment framework for geotechnical infrastructure particularly foundations. This framework is a multicriteria based that combines life cycle assessment, environmental impact assessment and cost benefit analysis and can be used at the planning and design stages of geotechnical projects.

In addition to these frameworks, there are several agencies such as the Bureau of Reclamation, the United States Army Corps of Engineers, the Federal Emergency Management Agency, and numerous cities such as the City of Boise that employ individual assessment methods for both sustainability and resiliency.

2.1.4 Drawbacks to Current Sustainability Frameworks

Generally, most sustainability frameworks follow a similar format to those previously mentioned. Sustainability assessments can include all three pillars in the triple bottom line approach, or only focus on a single impact such as emissions produced. If a framework only accounts for one pillar of the Triple Bottom Line, then the other aspects are being neglected and the assessment maybe inaccurate. Some sustainability frameworks, such as the LCA, only account for regular, or planned maintenance and operation. As a result, the framework is unable to capture the occurrence of an uncertain event, or the probability of failure given the risk of a catastrophic event. Sustainability frameworks as outlined here, cannot capture the resiliency of civil infrastructure.

2.2 Resiliency Frameworks

To measure the resiliency of civil infrastructure, frameworks often consider the response of the system given the occurrence of a catastrophic event. Generally, resiliency assessments take into consideration the change in functionality of a system given the occurrence of a catastrophic event. Measuring the response of a system or the change of functionality is often performed by quantifying the pillars of resiliency. Several researchers have outlined methods to compute resiliency, specifically, Cimellaro, et al. (2010) provide a detailed overview of multiple frameworks and quantification methods.

One particular method to measure this is the Driver, Pressure, State, Impact and Response (DPSIR) of the system. The DPSIR method was developed by the European Environment Agency (2018). Drivers are the forces that motivate social actions, or the pursuit of human needs such as food, water, shelter, health, security, and culture (Lee & Basu 2017). Pressures are threats or potential hazards civil infrastructure may encounter, these include natural hazards such as earthquakes, hurricanes, floods or health pandemics, as well as human-caused hazards such as terrorist attacks including cyber-attacks. The state of the system is characterized by the pillars of resiliency, mentioned and defined previously. Each pillar of resiliency is measured to reflect how a system may respond to a catastrophic event, for example a dilapidated roadway in need of significant repair will respond less effectively than a similar roadway that maintains a high-level of service. Impacts are the measurable effects upon the infrastructure given the occurrence of a catastrophic event, such as the percentage of roadway left unserviceable preceding a serious flooding event. Responses are listed as being the ability to restore service after a catastrophic event. The DPSIR assessment is evident in most resiliency frameworks and can be adaptable to almost any infrastructure. For example, utilizing the DPSIR method Lee & Basu (2017) performed a resiliency analysis on a transportation system. Their work consisted of a case study of a complex transportation system, which was subject to failure given various flooding scenarios.

2.2.1 Drawbacks to Resiliency Frameworks

Methods for assessing the resiliency of civil infrastructure have been developed by several researchers, and generally for very specific systems under specific hazard types. For example, Chang and Shinozuka (2004) discuss a quantitative resiliency framework for water systems while Davidson and Cagnan (2007) developed a model for an electric power system to recover from an earthquake. This allows for explicit analysis of specific types of infrastructure but prevents utilization of these frameworks on other systems. In addition, none of the current resiliency frameworks have provisions to account for impacts on sustainability caused by restoration activities.

2.3 Unified Approaches

There are, however, very few frameworks that account for both sustainability and resiliency assessments. Bocchini et al., (2014) attempted to develop a unified approach to sustainability and resiliency by analysing several bridges and Das et al. (2019) for pavement applications especially in sulfate-rich expansive clays. This framework also does not account for risk of hazard primarily because expansive soils are an ever-present danger to infrastructure.

Risk based frameworks are typically specific to a certain type of infrastructure or investigate only one type of failure. Lounis and McAllister (2016) developed a risk-based decision-making approach for combined sustainability and resiliency assessment for structural infrastructure. However, this framework does not account for the societal impacts under sustainability assessments. Further, risk-based approaches, especially in case of standalone resiliency frameworks, tend to be overly complex or highly reliant on computational analysis using sophisticated software (Cimellaro et al., 2010; Donovan and Work, 2017; Karamlou et al., 2017).

2.4 Risk

When designing civil infrastructure, considering the risk of failure is paramount to ensure the safety, security and durability of the built environment. As per Leps, (1987), and then later reemphasized by Christian, (2004), "*…if one actually thinks he knows where failure is most apt to occur, he is completely derelict if he has not provided a design which would eliminate such possibility*". For S&R assessments, the value in accounting for risk is that risk has a close relationship with the concept of resiliency. Also, sustainability is fundamentally connected to the concept of resiliency and thus inherently connected to risk. For the purpose of this paper, the definition of risk is the same as that of the United States Army Corps of Engineers' (USACE) definition, where risk is a measure of the probability and severity of undesirable consequences (U.S. Army Corps of Engineers 2012; USACE Institute for Water Resources 2018).

In an attempt to unify resiliency and sustainability assessments with the probabilistic risk-based approach, Frangopol and Yang, (2017) used LCA to determine the level of resiliency given the occurrence of a low probable high consequence event. The probabilistic approach can be assumed to be the likelihood of occurrence of a catastrophic event, paired with the probability of failure given the occurrence of the specific event. This concept was expanded by Lounis & McAllister (2016) where they used a form of Life Cycle Cost Analysis (LCCA) to determine S&R impacts and attempted to build a risk-based framework to capture impacts. However, even though the aforementioned frameworks considered risk as a fundamental component, both frameworks lacked actual unification between sustainability and resiliency as proposed by Bocchini et al. (2014).

3. Proposed Framework

To account for the numerous details and issues with S&R frameworks that have been previously identified, this paper proposes a risk-based framework that is simple and comprehensive enough to be used by engineers as a practical tool to assist with infrastructure design. This proposed framework measures the S&R of civil infrastructure based on the perceived risk of catastrophic events. This framework is intended to be adaptive and can account for numerous input parameters which plots the resulting S&R index values for clear representation of the current state of the infrastructure.

The work presented here is a continuation of the work published by Robbins et al. (2017), where the feasibility of developing a unified S&R assessment framework focusing on the impact of earthquakes on earthen dams. Similar to the framework proposed by Lounis and McAllister, (2016), the framework proposed here is based on LCA and uses a Bayesian approach to compute the probability of failure given the occurrence of a catastrophic event. However, the method of assessment presented here explicitly unifies sustainability assessment with the resiliency assessment while considering the risk associated for both assessments. This is unique as this framework considers the probability of failure for both S&R, such that an increased risk of failure may impact the overall sustainability of said infrastructure. An overview of the framework is presented in Figure 2. This framework follows a simple flow chart method to systematically assess both sustainability, with explicit descriptions of each step within the chart, then the results are graphically presented to provide a clear representation of the overall assessment of S&R, Figure 3.

3.1 Framework Steps

This framework assesses quality of an infrastructure as a function of sustainability, resiliency, and the risk of a catastrophic event. Here it should be noted that risk includes both the likelihood of occurrence and its consequence.

$$\text{"}Quality\ of\ Infrastructure\text{"} = f(sustainability, resiliency, risk)$$

The first step in this framework is to determine the system to be analysed. This system could be a school/ office building or water or wastewater treatment plant or a dam or any similar civil infrastructure. An example using a dam is presented in this paper but this process could be used on any similar infrastructure. Next step in the analysis is to utilize the triple bottom line approach to determine how sustainable the system is, and report the values in terms of dollars per year ($/yr.) as shown in Figure 4. Next, determine a probable hazard that could negatively impact the system, i.e. fire, flood, hurricane, earthquake. Determine the resiliency of the system in consideration of the probable hazard, and report as a scaled percentage. Normalization of these values is integral in the framework as this is the most applicable way to relate seemingly unrelatable indexes. Upon normalization, the values where then compared as percentages and compared to each other. Next, perform a second sustainability analysis to determine how the restoration activities (to regain functionality) affect the triple bottom line of sustainability of the system. Further discussion on this process is outlined later in this paper. Next, plot results graphically on a sustainability vs resiliency space (Figure 4) to help visualize the sustainability and resiliency indices. Steps to perform the computations for the sustainability index are show in Figure 5, and the steps for the resiliency index computations are shown in Figure 6. The quadrant in which the system falls in determines its S&R impact.

4. Example of Proposed Framework

To demonstrate the effectiveness of the proposed framework, we have chosen to model an earthen dam. This decision was based on the lack of S&R frameworks which focus on geotechnical engineering, especially considering geotechnical engineering is generally the first work to be performed for most types of construction which in turn has a significant impact on the overall S&R of infrastructure. To accommodate this study, Lucky Peak Dam near Boise, Idaho was analysed.

4.1 Background on Lucky Peak

The dam selected for analysis was Lucky Peak Dam, which is a rock-filled earthen dam located to the east of Boise, ID. Lucky Peak Dam is designed for flood control purposes and is owned by the USACE. The dam was constructed in the late 1940s by the Morrison-Knudson (MK) Company under contract to USACE. The dam spans approximately 305 m. at the crest, and reaches a maximum height of 106.7 m. The external geometry of the dam was obtained through literature, and the material properties obtained from the USACE (Northwestern University, 1976; US Army Corps of Engineers, 1948a; b, 2017). The internal geometry was assumed based on making comparisons of other earthen dams that were constructed at the same time period, for the same purpose, and by the same construction company as Lucky Peak. The reservoir behind the dam at maximum capacity contains approximately 0.4 cubic kilometres. of water (US Army Corps of Engineers, 2017). Historical data was collected on the recreational use of the reservoir as well as the average annual power production from the hydroelectric facility within the dam.

4.2 Modelling the System

Computational software was used to model the earthen dam such that seepage and slope stability could be shown to mimic realistic scenarios given varied saturation levels within the dam, as well as during and after seismic events. Currently there are numerous methods and types of software available to model civil infrastructure, however, for the purpose of this paper and in order to maintain simplicity, the software chosen to perform computations was GeoStudio, which allowed input such as material properties as well as surcharge loading, transient seepage analysis, static, and dynamic slope stability (GEO-SLOPE International Ltd, 2016). Two models were created, one to model seismic loads applied to the dam, and another to model a rapid-drawdown scenario. Using the provided material properties from the USACE, the internal geometry was modelled to have an impervious clay layer, a random layer of fill material, and a protective shell layer of coarse aggregate. Additionally, a porous layer on the downstream side of the dam was modelled to allow for drainage through the dam and directed to the toe of the dam. A foundation with a key cut at the base of the clay layer to mimic actual designs common in 1949, Figure 7. Material properties provided by USACE gave both design values, and actual. Variation between design and actual values were inputted into the model as parameters for Monte Carlo simulations. The hydraulic conductivity, porosity, moisture content, and pore water presser were required to perform the internal seepage velocity analysis were assumed by the 'generic' values provided in software. The software GeoStudio assumes the values on these other design parameters based on user-defined particle size, which in this simulation were obtained from historical data. The primary material properties used are shown in Table 1.

For the seismic analysis, seepage through the dam was modelled during the maximum capacity of the dam during normal operation. During modelling of the rapid-drawdown scenario, reservoir levels mimicked probabilistic flood events. The seepage analysis reported the internal effective stress, and pore water pressure was used as input parameters for the slope stability computations. Although there are numerous methods to analyse slope stability, the authors of this paper decided to use a generic and well-known method. For all models, slope stability was calculated by use of the Bishop's method of slices, as outlined in Budhu (2011). This method considered individual slices cut within the slope and bounded by a circle with varied radii. Each slice is then determined to have a mass, weight, and shear capacity associated with it. Then all slices are summed together, and the resulting Factor of Safety (FS) is computed by the ratio of available shear strength of the soil, by the required shear strength to maintain stability.

Variations in properties such as internal friction angle, moisture content, and unit weight, were accounted for in the Monte Carlo simulation to produce a probability density function which reported the "most likely" FS. These variations in material properties were determined by the changes in internal forces within the earthen dam based on location of the phreatic surface. For the seismic analysis an initial static analysis for both seepage and slope stability was performed before and after the seismic event. This showed any changes in internal seepage and slope stability after the seismic event. For the seismic analysis, a pseudo-static analysis was performed using a Peak Horizontal Accelerations (PHA) were obtained from United States Geological Survey (USGS), as well as the probabilistic data on the likelihood of occurrence for an earthquake in the Lucky Peak region (USGS, 2017). For the rapid-drawdown modelling, probability and magnitude of flooding was obtained from USACE Boise River discharge flow chart.

4.3 Sustainability Model

Sustainability calculations used input factors that were conservatively assumed. Assumptions were required, as actual data was not available for the research group. In consideration of this, the given input was assumed with known variance, and listed with corresponding resources where the data was obtained. Input values included the overall material volume for each layer within the dam, the money collected from recreational use of the dam and corresponding facilities, flood control damage, construction costs, construction timeframe, and any other value revolved around environmental, social or economic impacts. To relate all sustainability impacts into one single index value, each pillar of sustainability was normalized as dollars per year ($/yr.).

4.3.1 Environmental Impacts

The environmental impacts of building a dam are numerous and varied, ranging from changes to the spawning habitats of fish to the downstream erosion due to changes to sediment loads in the river. Capturing these impacts requires expertise in biological, geological, and hydraulic sciences, as well as in-depth knowledge of the regular day to day operations of the facility. For this example, the analysis of environmental impacts of the dam are limited to the impacts due to the construction of the dam. A more detailed example would account for all the wide-ranging impacts of building a dam, as well as the regular operations and maintenance during the regular lifecycle of the dam. In order to reduce the level of effort to a manageable work load, the authors of this paper chose to neglect these potential impacts, however it is recognized that owners and stake holders of such a system may be concerned with these impacts and may choose to consider them in their own analysis. This paper simply provides the framework to allow for such an analysis, although the authors have chosen to neglect them here.

Although there are numerous metrics available for measuring the environmental pillar of sustainability, such as flora, fauna, the chemical composition of leachate, or emissions from construction, this research chose to use total Embodied Energy (EE), and Embodied Carbon (EC) from construction activities for analysis. Total EE and EC were quantified by identifying all emission sources during construction including vehicles and equipment used to excavate, quarry, and construct the dam. To measure the use of vehicles during construction, the total material required to construct the dam was estimated by using the internal and external geometry. Once the initial model was established material volumes were computed. Using the volume of each section within the dam, (random, clay layer, external shell), the average unit weights reported by USACE were used to determine the mass and weight of each section.

Material weight was used to determine the required number of vehicles, and trips per vehicle required to excavate, transport, and compact the material to the proper density for the dam. Emissions produced from quarrying activities were calculated by use of the Environmental Protection Agency's quarrying emissions spreadsheet, (U.S Environmental Protection Agency 2016). Vehicle information for all construction activities were obtained from Caterpillar Inc. (Caterpillar Inc., 2015, 2017a; b; c). Using average excavator cycle times, horsepower, fuel consumption and haul capacity, emissions produced from each construction activity were determined. Computations included fuel consumption based on the time required to complete each construction activity given the material volume and density. Conversion from vehicular horsepower to pounds of emissions was computed by use of Equation 1. Emissions where then computed by multiplying emission factors to fuel consumed during each construction activity (EPA, 2014; Office of Transportation and Air Quality US EPA, 2008).

Equation 1: Horsepower conversion formula, used for emissions generated by vehicles

$$\left[\frac{lbs}{hr}\right] = \left[\frac{g}{bhp\_hr}\right] x \; bhp_{max} \; x \frac{1lb}{454g} \qquad (1).$$

4.3.2 Social Impacts

Arguably one of the more difficult sustainability metrics to quantify are the ones that revolve around social impacts. As a response to this difficulty, a commonality among most S&R assessment frameworks is to neglect the social impacts, as exemplified in work by Lounis and McAllister (2016). When considering civil infrastructure, the views on who may benefit and who may be disadvantaged from the construction of infrastructure may at times be vague. This concept may be difficult to fully understand and quantify but becomes clearer in scenarios where customers pay for a service. Earthen dams constructed for flood control are considered a benefit to society such that they protect property from damage by floods, as well as potentially produce power from hydroelectric facilities. This is a direct benefit to customers and property owners surrounding the dam. Some aspects may not be clear, such as if a person pays to use a facility for recreational use they are at an economic loss while the owners of such facility are at an economic gain. Further, customers who purchase recreational services gain intangible values, such as quality of life. Quantification of the intangible may be too subjective for practitioners; however, practitioners can use the preceding example as a guide to determine the value of key components if needed.

Benefits were quantified as the amount of money saved from flood damage, generation of hydroelectric power, and recreational use provided by the reservoir. An estimated 921,000 people per year use the recreational services of Lucky Peak, at a fee of $5.00 per carload and the average registration cost of $30.00 per 3.7 m. boat. Over the lifespan of the dam, an average value of property saved each year from flood control was estimated to be $1 million per year. Power output generated from the hydroelectric facility averages 322,000,000 kWh/year, (US Army Corps of Engineers. 2017). Disadvantages included loss of access to land due to the filling of the reservoir, where land costs an average of $18.62 per square kilometre (Northwestern University, 1976; USDA National Agricultural Statistics Service, 2017). Although the water stored in the reservoir would inevitably be used for other purposes, such as irrigation water, this was not considered for social impacts due to the diversion of irrigation waters performed by another dam further downstream from Lucky Peak.

4.3.3 Economic Impacts

Construction of Lucky Peak began in 1949 and lasted until 1955, when the dam became operational. The total cost of the construction at the time of completion was reported as $19 million. The documentation obtained during literature review on regular operation and maintenance (O&M) shows for the year 2015, Lucky Peak cost the Walla Walla district of USACE $2.2 million. Considering the issue of the original construction cost and the maintenance costs not being spent during the same time period, financial life cycle costs had to be performed to bring the past worth of construction costs up to present worth at the same time as the maintenance costs. The Internal Revenue Service's average annual inflation over the time period of the dam was estimated to be 3.5%, (IRS.gov, 2018). Using Equation 2, the annual worth of the dam was computed. This value was reported as the total economic impact given the construction of the dam, as well as total costs for operation and maintenance. Hydroelectric power was not computed as an economic benefit as it was considered a social impact.

Equation 2: Future value formula using present worth, interest rate and design life.

$$FV = PW\ (Cost, Interest\ Rate, Design\ Life) \qquad (2).$$

4.3.4 Sustainability Summary

After each pillar of sustainability was assessed the values were normalized to dollars per year ($/yr.). This allowed for all values from environmental, social and economic impacts to be summed together and reported as a single index value. Assumptions were made on several input factors for the sustainability assessment. This was required as actual data on certain key components were not available to the researchers. Further assumptions had to be made on benefits and burdens for social impacts. Although these assumptions may generate scepticism in the results, they highlight the versatility of the framework. This is due to the ability of the framework to collect and analyse any input parameter available for assessment and how the user-defined input directly related to the results of the assessment.

4.4 Resiliency Model

All pillars of resiliency were considered for computation, except for redundancy. This is due to the fact it is not logistically or economically feasible to construct a redundant dam near Lucky Peak. Redundancy calculations can be performed on other systems where an alternative, or secondary component is feasible. In order to compute the resiliency component of the framework, a specific hazard event had to be chosen for analysis. For this study two potential catalysts to failure were analysed by measuring the predominant change in the strength of the structure after the event. Two models were constructed, one for seismic impact, and another for flooding/rapid-drawdown. To determine the proper earthquake magnitude and peak horizontal acceleration for potential near or around the Lucky Peak Dam area, data was obtained from the USGS website, (USGS, 2017). For rapid-drawdown, the magnitude of flooding events as well as reservoir level were determined from USACE Boise River discharge flow chart. The probability of failure was then used in a Bayesian approach, Equation (3), to relate the probability of occurrence of an earthquake, and output is given from Monte Carlo simulations.

Equation 3: Bayesian Approach formula

$$P(A \mid B) = (P(B \mid A) * P(A))/(P(B)) \qquad (3).$$

4.4.1 Robustness

As per the definition previously outlined, robustness is the ability of a system, or civil infrastructure to absorb an impact, or withstand significant damage from a catastrophic event. For this research the change Factor of Safety (FS) is a measure used to determine the ability of the system to withstand impact or the strength of the system. The change in the slope stability was used as the measure of strength. By use of software, models were created for both seismic and flooding events.

The seismic analysis used Peak Horizontal Accelerations (PHA) which were input into the software for each corresponding earthquake that could potentially occur. Five earthquake scenarios were selected as being possible, magnitude 5, 5.5, 6, 6.5 and 7 on the Modified Mercalli scale. These magnitudes were chosen because a magnitude less than 5 observed little to no change in the FS, and magnitudes larger than 7 are not listed as being probable to the Lucky Peak area. Incrementing magnitudes by 0.5 was chosen to reduce computational time. Given the variability of construction material properties, Monte Carlo simulation was performed during the slope stability calculations. The resulting FS produced from each simulation was the mean value reported from the probability density function listing as the most probable given the variations in material properties. The change in FS from the static slope stability analysis to the FS after a seismic event was considered to be a percentage loss of functionality of the dam. Using the probability of failure and the probability of occurrence of the associated earthquake a total probability of failure was calculated. Robustness was then reported as the compliment of the total probability of failure.

Flooding scenarios were modelled as having a rapid-drawdown effect to the dam. This was considered as if a flood occurred, an uncontrolled release may be possible due to erosion of an unimproved overflow spillway located at Lucky Peak. For the analysis, a transient model was used where the water level is initially at the maximum level of the dam, then over the course of a few days the retained water was released. The hazard of rapid-drawdown includes loss of stabilizing effect from the water on the upstream side of the dam. This water acts as a surcharge load and pushes down on the face of the dam. When the reservoir water drains, the dissipation of pore-water pressure is highly influenced by the permeability and material properties of the embankment fill. The lower the permeability of the soil, the longer the soil takes to drain. If water is retained within the soil after the drawdown, the effective shear strength of the soil decreases which makes the slope susceptible to sliding and catastrophic failure. The next component of analysis is to perform a slope stability computation on the upstream face of the dam. This is to analyse the shear strength of the saturated soil, before the water has had sufficient time to drain out of the dam. Several models were performed, each with varied initial depth of the reservoir and time durations of the drawdown. Drawdown time that exceeded 30 days was deemed sufficient to maintain slope stability, however anything less than 15 days proved to be catastrophic. To model a potentially catastrophic scenario, the drawdown time was determined to be between 3 and 5 days, with a probability of occurrence ranging between 0 and 500 years. Results are listed in Table 3.

4.4.2 Resourcefulness

After each modelled earthquake and robustness calculation, the resourcefulness of the structure was determined. 100% functionality was assumed as the required objective for the rehabilitation efforts. In this analysis, resourcefulness was simplified to include materials required for rehabilitation efforts which implicitly includes project personnel's ability to locate and procure these materials in an efficient manner. It should be noted here that this a very simplified approach of accounting for resourcefulness which in essence is the ability of the project personnel to be resourceful during rehabilitation efforts. It was also assumed that the required amount of material for rehabilitation was proportional to the amount of damage as indicated by the failure slip circle, as shown in Figure 8. This assumption was made as the identified slip circle was where the most probable failure could occur, as this is the location where shear strength is not sufficient to sustain the loading applied by the material above the circle plane. For each slip circle drawn from the slope stability calculations the required material volume to complete rehabilitation was computed. This was performed by taking the area of the slip circle and then multiplying that area to the length of the dam. The volume of material required could then be directly related to the vehicular effort to excavate, transport, and compact the material to the original slope and density. Cost of the material and fuel to rehabilitate the structure after an earthquake could then be computed. Using the Walla Walla district for the USACE legislative budget, the cost of repairs was correlated to the available budget. Equation 4 was used to determine a percentage of the budget that the repairs required. This percentage was then related to the probability of occurrence of the associated earthquake, and a total probability was computed, similar to the robustness calculations.

Equation 4: Resources equation

$$\text{Available budget} = ((\text{supply}-\text{demand}))/\text{demand} \qquad (4).$$

4.4.3 Rapidity

Rapidity as defined earlier is the ability to reinstate functionality in a timely manner which requires a systems level approach and depends heavily on time. Rapidity assessments should include all aspects that contribute to the pace of rehabilitation efforts that take into account policy, decision making, bidding process, reconstruction time and other aspects. In this example, reconstruction time using the materials required for rehabilitation efforts was used to quantify rapidity. The reconstruction time only accounts for the time required to rebuild the dam but not the reconstruction of affected infrastructure downstream. It should be noted here that this is a simplified approach to quantify rapidity. However, this simplification does not hinder the demonstration of the proposed framework, which is the main purpose of this example.

Using material quantities required for rehabilitation efforts, the time to excavate, transport and compact the material to required density was calculated based on standard vehicle operation speed and load capacity. The rehabilitation was determined to be continuous immediately following a disastrous event. The time required to complete the rehabilitation was then normalized to the original construction time, and the total probability of the time required was computed using the probability of occurrence for each earthquake scenario, and flooding event. The results were reported as a percentage similar to that of the robustness calculations.

4.4.4 Sustainability Impact Following Catastrophic Event

If the system was allowed to fail and not in any way reconstructed after the hazardous impact, then there would be no additional considerations for sustainable impacts. However, due to the assumed effort to rehabilitate the system, an additional sustainability analysis was required. This is due to the fact that in the event of a hazardous impact, the effort to rehabilitate the system would create new emissions that were not previously considered during the regular life cycle of the system. Considering the rehabilitation efforts require vehicular use, money, and additional materials, a second sustainability impact assessment needed to be computed. This second sustainability assessment is one of the aspects that sets this framework apart from others. To consider the level at which a hazardous event impacts the sustainability of a system is required to fully grasp the sustainability of a system. If the infrastructure is severely damaged after the impact that rehabilitation is excessively burdensome on resources, then that system is not considered sustainable. The hazard-related sustainability assessment was performed similarly to the first. The methods of assessment used the material volume from the failed slip circle to determine vehicle work, time of construction and emissions. Cost and social impacts were included in simplified resourcefulness calculations. Fuel consumption, which relates to embodied energy and emissions produced to rehabilitate the earthen dam in the event of a catastrophic event, were all normalized to the original sustainability output values. Similarly, to all the other resiliency calculations, the additional sustainability calculations were reported as a total probability given the occurrence of an earthquake and normalized to a scale of one-fifth of the total resiliency of the system.

4.4.5 Resiliency Summary

Resiliency computations were performed with a medium that is common to most engineering firms, and students. The chosen platform for computational analysis was a standard spreadsheet, where input values could be linked to computational cells then output results in another cell. The reason for using this method was to ensure that the calculations could be performed easily, and useable by industry. Modelling the potential failure scenarios took basic input values that would normally be obtained by any design firm, or engineering entity that would be performing conventional design work, and then used that information to determine what the change in the designed FS after impact from a catastrophic event. Resiliency analysis had a primary focus on two separate failure modes, one for potential earthquakes and another for rapid-drawdown. Both analysis methods used slope stability as the predominant measure for FS. The seismic analysis performed consisted of modelling several potential earthquakes that could occur at the location of the dam, and determining what change occurred in the slope stability after such impact. The rapid-drawdown scenario modelled several flooding events, and time durations required to draw down the reservoir and how this event impacted the upstream slope stability. Each failure analysis was discretely computed to give a clear picture of the quality of the entire dam.

5. Results

All calculations were performed using standard input values that were assumed to be readily available to any design firm, or decisionmaker that would be considering the S&R quality of civil infrastructure. These values included costs, benefits, the total output of energy and use of machines and equipment. Availability of information directly relates to the accuracy of the results. This is evident in how the user-defined input values, such as costs and material used have such a significant impact on how the results are outputted. The final S&R results are listed as discrete values; however, this is more of a theoretical value rather than an actual value. As anyone who has worked in financial planning or acquisitions understands, it is very difficult to precisely predict costs of construction until the project is underway. Current industry standards are to use general values, that have associated ranges as input to make bids on projects. These ranged values then have a compounding effect on the results, as the actual value may be slightly different. Considering that this framework uses costs, emissions, material strength parameters and is extended over the course of several decades, the complexity of the values makes it difficult to accurately predict the results. To alleviate having to account for this complexity, the input values are listed as user-defined. This prevents fixed ranges, scope, or weighted factors to the framework, which allows for flexibility of use from high-level decision makers, to intricate designers who have intimate details of each aspect on the project.

5.1 Sustainability Index Value

All sustainability calculations were normalized to dollars per year ($/yr.). This made all output values from every metric within sustainability computations relatable and ensured all outputs could easily be understood without an engineering background. For both the seismic analysis and the rapid-drawdown analysis, the sustainability calculations remained the same. This assumption was made based on the original design and material used for the dam, as for each scenario the original construction would take place as outlined by USACE. Sustainability results were scaled that allowed for the x-axis scale to vary with the magnitude of the project. This means that as the overall costs, or benefits of the project increase or decrease, the scale is normalized to a range that would accurately depict the results in relation to the overall value of the project. Individual values for the sustainability results are listed in Table 4. The overall index was summed to be ***$41,165,000 per year***.

5.2 Resiliency Index Value

As previously mentioned, the resiliency computations were broken up into two discrete analyses. This was to determine if changing the failure mode would change the overall S&R rating of the system, and to determine the framework's flexibility in analysing multiple failure modes. The results provided validation that the framework can assess the resiliency of civil infrastructure and is robust enough to analyse any failure mode so long as changes in FS and material use to rehabilitate the system are determined. Similar to the sustainability computations, input parameters were determined based on the assumption that the user would have access to specific information that would be required to rehabilitate the system in the event of failure. This information included the methods to rehabilitate the system, as well as how to perform functionality checks on the system to ensure structural integrity. Each pillar of resiliency was determined to be one-fifth of the overall resiliency rating. This means that each result from the resiliency calculations had to be scaled from -20 to 20 using linear interpolation, then summed all together to get a resiliency index that falls between -100 and 100. Note that the difference in results from the seismic analysis and the rapid-drawdown could be due to the physical properties of the construction materials. Given that a rapid-drawdown event leaves a large portion of the internal structure of the dam saturated, as well as a reduction of the surcharge loading on the upstream face of the dam caused by the loss of the water. This loss of strength then corresponds to a significant loss of slope stability, thus reduction in overall FS.

5.2.1 Graphical Representation

As previously mentioned, the results of the S&R computations are represented in a format that is clear and readable by anyone that may, or may not, have engineering training or background. The results are listed on a graph with a basic cartesian coordinate system, where the first quadrant represents the most desirable system which is both sustainable and resilient, the second and fourth quadrants indicate cautionary areas, and the third quadrant represents a system that is neither sustainable nor resilient. The graphical representation is intended to be used so that decision makers can quickly and easily see the ranking S&R index as compared to alternative designs, or failure modes. Figure 9 shows the graphical results from the analysis of seismic and rapid-drawdown of Lucky Peak.

6. Conclusions

From the discussion at the beginning of this paper, it is apparent that there is a movement within the civil engineering industry towards considerations of sustainable development and resilient design. Many papers, researchers, agencies and municipalities are considering S&R as a forethought to all major construction activities, and it is expected that more will continue with this trend. With current development in this form of engineering philosophy, it is paramount that tangible and pragmatic S&R frameworks are developed. There are currently numerous frameworks in existence, as previously mentioned, but few offer a methodology that is clear and concise enough to be replicated beyond an academic setting. The main purpose of the paper is to provide a framework that is practical and realistic such that current engineers and policy makers are able to obtain this framework and assess the S&R of civil infrastructure. This paper discussed the basic overview, methods and concepts that are required to utilize this framework as well as provide an example demonstrating the use of the framework for assessing a civil infrastructure. The following paragraphs summarize some of the assumptions made to complete this work along with the main highlights of the framework and its relevancy.

Novel aspects of this framework revolve around the simplicity, and flexibility of the framework. Major input parameters are user-defined, which allows for a wide range of variable to be considered when determining the overall quality of the infrastructure. The flexibility of the framework allows users to input the design parameters at any level of complexity that is available to them. For example, if a user has general information of a system and only can input basic or averaged input values, the results are still output in a format that may provide a general understanding of the S&R index of that system. Further, if a user has intimate knowledge of the infrastructure, such as having performed either sustainability or resiliency assessment using another framework or methods or they have explicit data detailing every aspect of the system, that information may be input as usable data into this framework. Either way, the framework output is provided in a way that is understandable, gaining precision and accuracy with the addition of more input data.

Without the exact data on how the Lucky Peak dam was constructed, the internal geometry, social impacts or the total property worth saved from flooding by the existence of the dam, many assumptions would have had to be made for this work. For example, hydro power was a benefit for social in this framework, however if that same unit was assumed to be any other impact, such as a cost to the facility, the sustainability results would have been skewed in another direction. Also, the spillway to the south of the dam was not considered in the computations, which is not explicitly a component of the Lucky Peak dam but is an overall component to the functionality of the system. Without the overflow spillway, the potential for overtopping increases. The scope of the framework is dependent upon user-defined parameters, such that in this work we chose to neglect the spillway, but other researchers may choose to include it. The framework will allow for either method of analysis, but it must be noted that the results will change based on the overall scope chosen for analysis.

Resiliency computations are predominantly dependent on changes in functionality over time after the occurrence of a major impact. Methods to determine this change in functionality could be as flexible as the user decides, such that any preferential modelling software, or simulations could be used so long as the change in FS, and the probability of occurrence are determined. For this research the modelling software used was Geo-Studio. However, for modelling the flood scenarios software that models water flow over the geological surface could have been used. For seismic analysis almost any finite element software could be used. Alternative modelling software allowed by the framework so long as the probability of occurrence for each scenario is obtainable and the resulting output is used is reported in a format useable in the Bayesian analysis.

Further development of the framework could consist of expanding the applicability beyond geotechnical systems. Primary focus on this work was to develop the preliminary framework so that future researchers may be able to use this as a tool to expand on and adapt to their own systems. Transferability of results from one single index value for sustainability and one for resiliency is acceptable for now, but future work may push to unify the indices into one index. Further, unification of this framework with existing sustainability frameworks would be beneficial for systems that already employ certifications in development, such as a LEED rating.

From the discussion in the preceding paragraphs, the framework is capable of being both simple, flexible, and robust enough to warrant use on major civil infrastructure projects.

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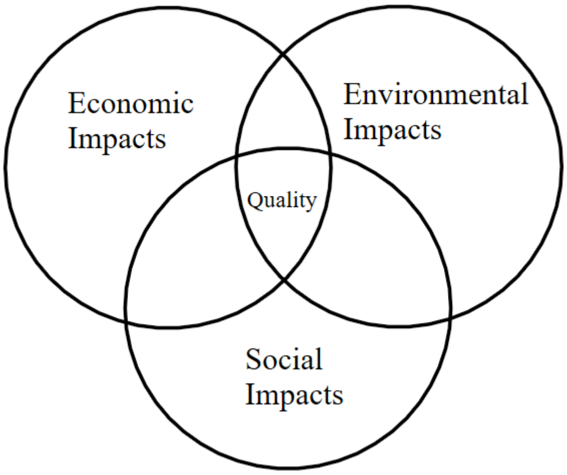

Figure 1: Vienne Diagram of relationships of the overall quality of a system

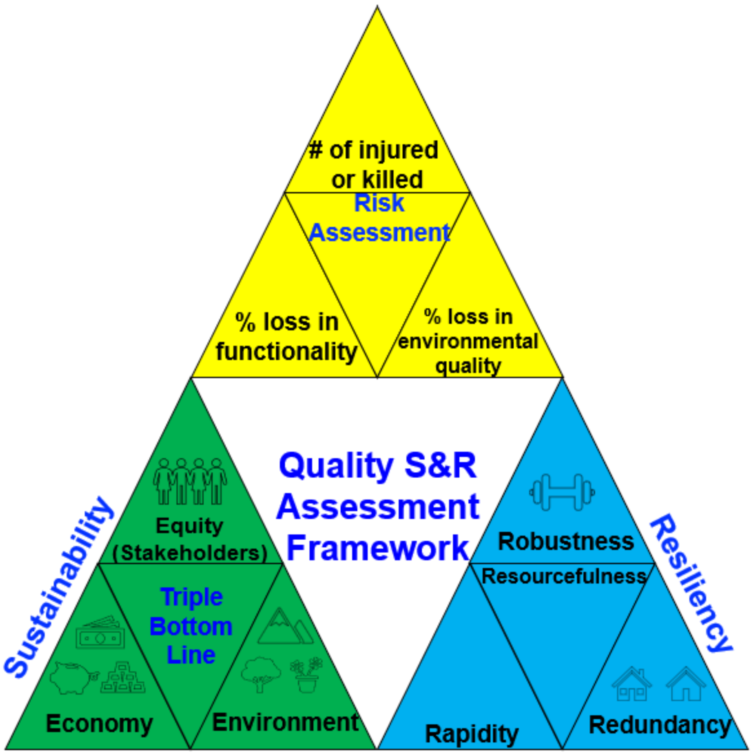

Figure 2: Overview of the proposed framework

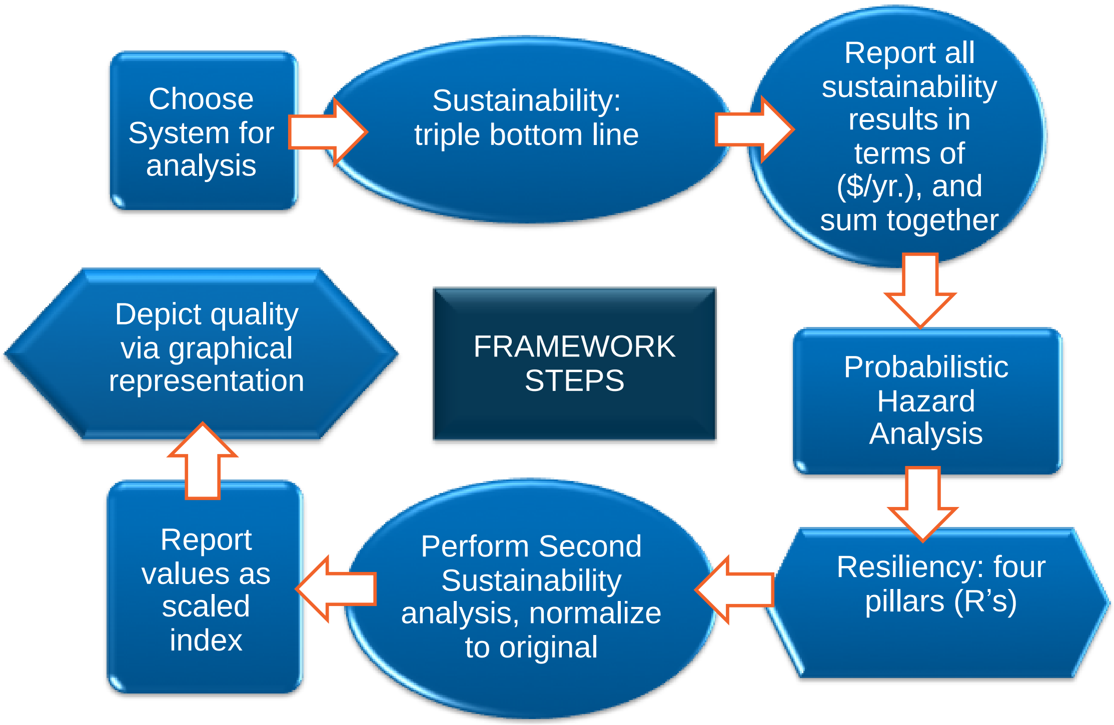

Figure 3: Flow chart depicting the analysis steps for the proposed S&R framework

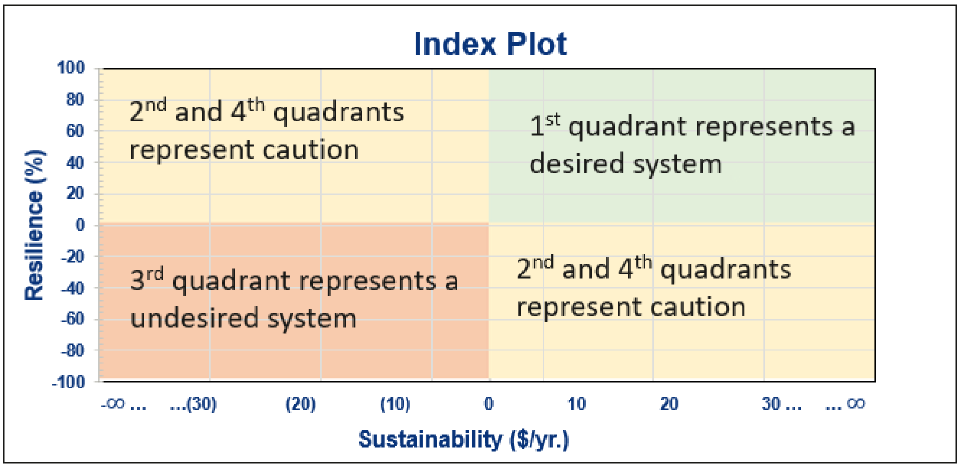

Figure 4: Graphical representation of S&R assessment results.

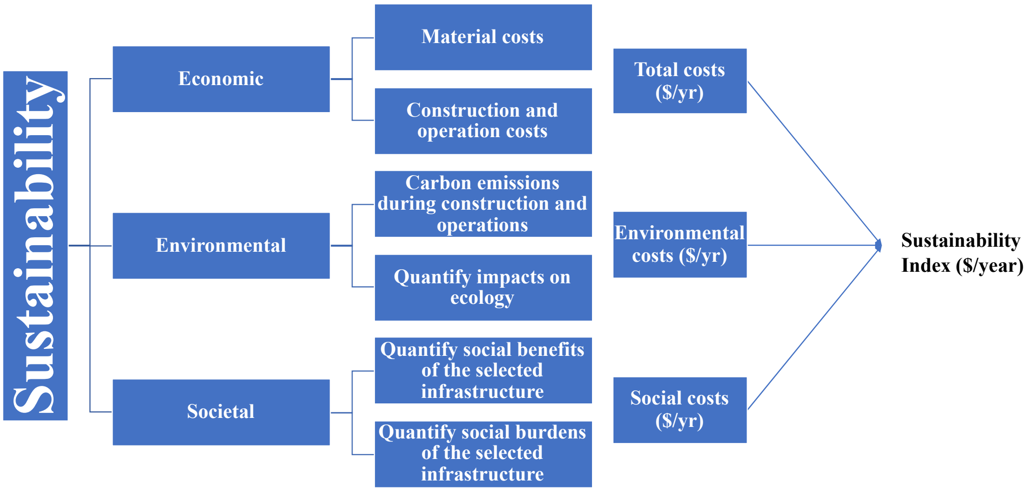

Figure 5: S&R framework steps showing quantification of sustainability

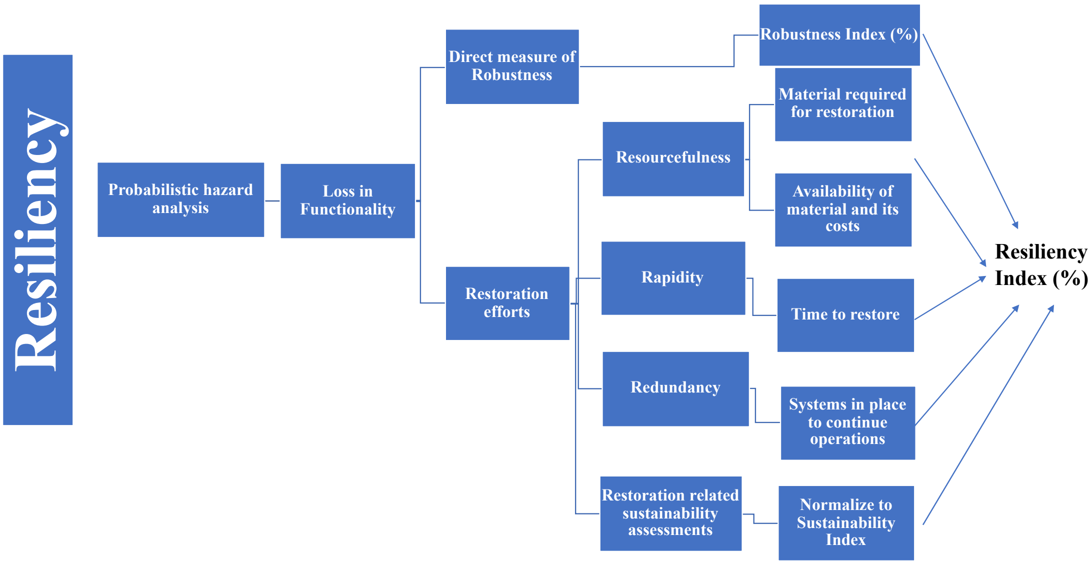

Figure 6: S&R framework steps showing quantification of resiliency

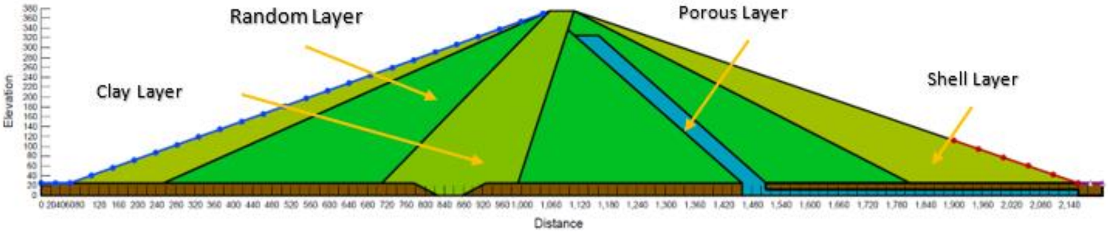

Figure 7: Model of Lucky Peak, showing internal geometry

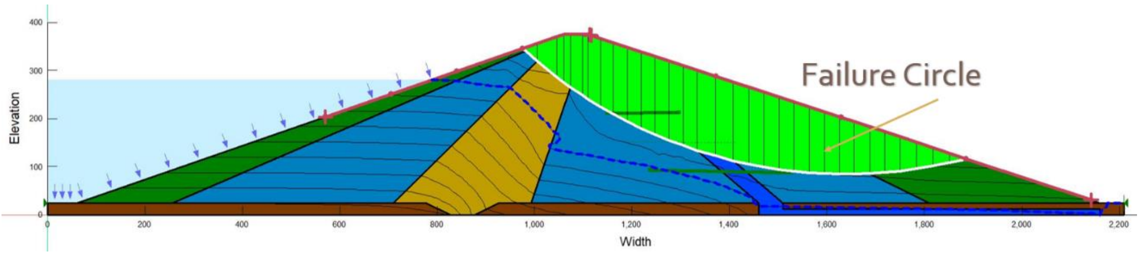

Figure 8: Slope analysis, slip circle failure plane

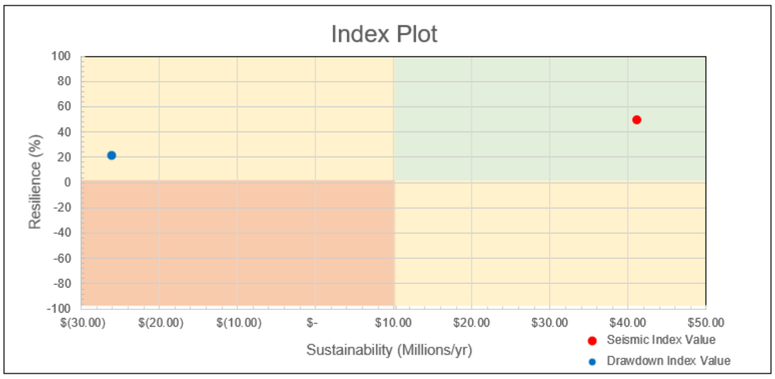

Figure 9: Graphical representation of both seismic analysis and rapid drawdown results