A UNIFIED RISK-BASED FRAMEWORK FOR ASSESSING SUSTAINABILITY AND RESILIENCY OF CIVIL INFRASTRUCTURE

by

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The following individuals read and discussed the thesis submitted by student Thomas Adam Robbins, and they evaluated his presentation and response to questions during the final oral examination. They found that the student passed the final oral examination.

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ABSTRACT

As of February 2019, the National Aeronautics and Space Administration (NASA) has reported since 1880 the average global temperature has increased 1°C, with the warmest year on record being 2016. As the years continue to pass, it is becoming more evident that climate change is occurring, which is known to be a catalyst for climatic weather events. Statistically speaking, these events are more prevalent, and catastrophic exemplified as hurricanes, earthquakes, flooding, and fires. In addition to the increase of potentially catastrophic events, society as a whole has become more conscientious in the use and preservation of natural resources, waste generation, and energy consumption. As the overall population continues to grow, the need for safe, secure and sustainable infrastructure increases. Civil infrastructure must be assessed to measure the level at which it will withstand impact from a catastrophic event, as well as how it is utilizing precious resources and energy.

In consideration of these previously mentioned issues, several federal agencies, companies, and researchers have put forth an effort to measure and quantify the ability of civil infrastructure to withstand climatic catastrophes. Also, metrics to quantify sustainable construction are increasingly used as a common tool for infrastructure design and development. Most sustainability metrics consider the qualities of a system that revolve around the concept of sustainable development but fail to consider the resiliency of that system. Sustainability assessments are often discrete and will focus on one particular aspect or measure. Resiliency metrics are often overly complex and do not

fully encapsulate the quality in a way that is pragmatic or useful to practitioners and engineers, or simply neglect sustainable construction methods.

Proposed here is a framework that attempts to unify sustainability and resiliency assessment of geotechnical infrastructure, by considering the risk of failure given the probability of a catastrophic event. The framework is developed for use on geotechnical engineered systems, specifically an earthen dam used for flood control. A Bayesian analysis is used to determine the probability of failure given the occurrence of a catastrophic event, in conjunction with both a resiliency assessment, and sustainability assessments. This is to ensure that the sustainability index is jointly dependent upon the changes in resiliency given the occurrence of a catastrophic event. Two separate failure modes that are possible at the location of the earthen dam were modeled to determine the flexibility of the framework. Failure modes include seismic events, and rapid-drawdown and both were modeled with their associated probabilities. Results from the assessment are represented as a single index value that is plotted on a cartesian coordinate system. It is of note that assessment of a particular form of infrastructure mandates analysis of particular failure modes, and changing the system then requires analysis of failure modes to that particular system. In order to fully encapsulate a unified framework for sustainability and resiliency, it was imperative that the thesis provided here focus on one particular infrastructure system, which was chosen to be an earthen dam.

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LIST OF ABBREVIATIONS

ASCE	American Society of Civil Engineers
bhp	Break Horse Power
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	Horse Power
ICE	Institution of Civil Engineers
K	Hydraulic Conductivity
lbs.	Pounds
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

CHAPTER ONE: GENERAL OVERVIEW OF PROJECT

Introduction

Historically, civil infrastructure has been fundamental in the development of the United States, as well as most other countries. This is supported by the clear ties between the economic success and construction of infrastructure. Examples are prolific throughout history, such as the development of the Erie Canal which was used to transport goods from the farms in the west, to the eastern consumers, to the interstate highway systems developed at the direction of D. Eisenhower, to the waterways, dams and irrigations systems developed by the Bureau of Reclamation. Civil infrastructure is tied to almost every aspect of modern life, as those who live in western cultures are dependent upon the amenities, luxuries and aspects afforded to us such as running water, flushing toilets, structurally-sound buildings and effective transportation systems. With each passing year, the United States increases in population, produces more domestic products, creates technology, and uses vast amounts of natural resources. Along with these changes there is an ever-increasing concern over the potential of failure given the threat of climate change, catastrophic natural disasters, geo-political turmoil, and the reduction of available natural resources. In response to some of these listed issues, engineers are beginning to experience a paradigm shift, where a focus on design and development of civil infrastructure incorporates means and methods to mitigate and prepare for potential failures that were not normally planned for through conventional design. One of the first movements forward to implement these considerations is to develop a type of screening process, or assessment framework to determine the functionality and durability of civil infrastructure, as compared to how well the system is capable of withstanding potential catastrophic impacts, or how well the system uses non-renewable resources.

Frameworks

Assessment frameworks are as prolific as the very infrastructure they are designed to assess. There exist numerous agencies that have attempted to measure or rate the quality of infrastructure, based on varied metrics or methods. Most of the frameworks that exist are focused on measuring the sustainability of a system, while some measure the resiliency of a system. Generally, the frameworks that exist to measure sustainability aspects of a system tend to focus on environmental, or economic impacts caused by the system. Resiliency frameworks generally attempt to measure the rate at which a system can rebound after impact from a catastrophic event, or in other words, how quickly the system can come back to full functionality after losing some specified amount of functionality. Considering the number of available frameworks, only a few are mentioned in this thesis. A brief introduction to some of the more widely accepted frameworks are listed below.

Sustainability Frameworks

Frameworks to assess sustainability cover a wide range of topics, such as material use, natural resource conservation, energy production/use, hazardous chemical emissions and social impacts. One of the more common methods to assess the sustainability of a system is to measure each potential impact and weight them based on the entire life cycle of the system. This method is often referred to as the Life Cycle Analysis, or if the assessment is focused on costs, it is called Life Cycle Cost Analysis.

Life Cycle Analysis

Generally, Life Cycle Analysis, (LCA) measures the overall impacts throughout the life of the system. Impacts may include any aspect that either has a negative, or positive effect due to the construction, use, or demolition of the infrastructure. Several frameworks exist to compute the LCA of a system, one of which is provided by Eckelman et al., (2014). This example used environmental and economic assessment methods specific to a water storage facility. A benefit as well as a 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 or associated weights.

Emission Factors

Agencies such as the United States Environmental Protection Agency (EPA), and Circular Ecology (Circular Ecology 2016; US Environmental Protection Agency 2017) use factors to quantify the environmental impact caused by civil infrastructure. The EPA has developed emission factors specific to sources such as vehicles, or processes that emit pollutants into the atmosphere (EPA 2014; Office of Transportation and Air Quality US EPA 2008). The 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. Emissions are determined based on fuel consumption from construction or operational activity. One aspect of measuring emissions is that the amount and type of emissions will vary as the fuel type and machine efficiency vary.

Infrastructure Specific Frameworks

The United States Green Building Council (USGBC) was formed in 1993, developing 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.

Another rating system similar to LEED is Greenroads. Greenroads is specific to transportation systems (Muench et al. 2011). Quantification of the sustainability of a system 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).

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

Drawbacks to Sustainability Frameworks

Generally, most sustainability frameworks follow a similar format to those previously mentioned. 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.

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, Reinhorn and Bruneau, (2010) provide a detailed overview of multiple frameworks and quantification methods.

One particular method to measure the resiliency of a system is the Driver, Pressure, State, Impact and Response (DPSIR) method. The DPSIR method was developed by the European Environment Agency (2018). As stated by Lee & Basu (2017) the DPSIR assessment is evident in most resiliency frameworks and can be adaptable to almost any infrastructure, however, it lacks the ability to assess the sustainability of a system.

Drawbacks to Resiliency Frameworks

Discrete methods of assessing the resiliency of civil infrastructure have been developed by several researchers, and generally for very specific systems. This allows for explicit analysis of specific types of infrastructure but prevents utilization of these frameworks on other systems. 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. Also, Das et al. (2016) used the slope stability of an earthen dam to determine the robustness of the dam. Other discrete frameworks exist but will not be mentioned here. 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 assessments by analyzing several bridges. The framework Bocchini et al., (2014) developed inherently neglected risk, or any form of probabilistic analysis. There are, however, several frameworks that account for risk. Risk based frameworks are typically specific to a certain type of infrastructure or investigate only one type of failure. Further, risk based approaches 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).

Research Objective and Tasks

In consideration of the issues mentioned about assessment frameworks, this thesis proposes a framework that is intended to provide engineers with a tool to assess civil infrastructure that is a risk-based, probabilistic and unified approach to assess both sustainability and resiliency. Research for this thesis is broken into four major areas, literature review, framework development, modeling a system, and publishing manuscripts as outlined by Figure 1.

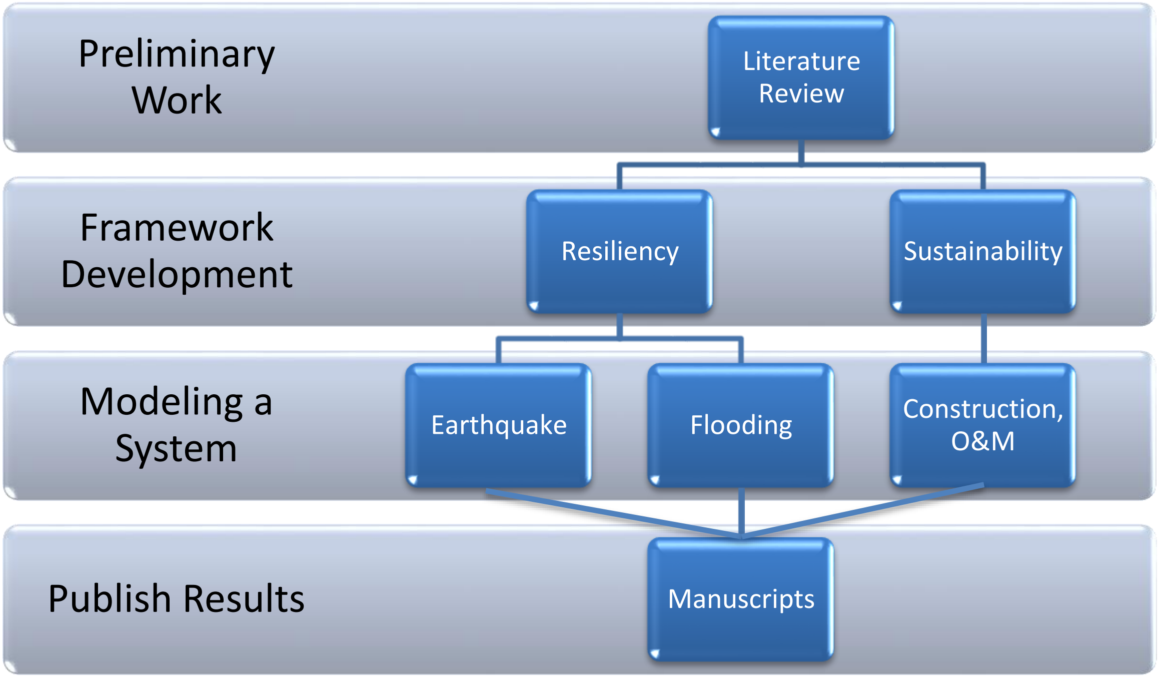

Figure 1: Thesis Research Objectives and Tasks

Manuscript Outline

Proposed here is work which was performed under the requirement to complete the Master of Science thesis-based program for Civil Engineering. This thesis is a pragmatic and unified, risk-based approach to assessing the sustainability and resiliency of civil infrastructure. This method is intended to alleviate the complexity from current frameworks yet be robust enough to fully assess the quality of civil infrastructure. Outlined within this thesis are two technical papers that explicitly cover the methods of analysis for the proposed assessment framework, then are followed by a final summary to conclude the thesis. Chapter two is the first publication that was presented at the International Foundations Congress and Equipment Expo (IFCEE) in 2018. This preliminary paper covered the general concept of unifying sustainability and resiliency. Chapter three covers the second paper which is to be published in a journal of respectable note at the end of the Spring 2019 semester, and chapter four covers a summary and conclusion of the entire thesis. Spreadsheets used for computations are attached in the appendix, as well as a hydrograph that was used to determine probable flooding scenarios for modeling.

CHAPTER TWO: PRELIMINARY WORK ON UNIFIED FRAMEWORK

Preliminary work on unified approach to sustainability and resiliency

As part of preliminary work on developing a framework for unifying sustainability and resiliency, a technical paper was published with the International Foundations Congress and Equipment Expo (IFCEE). This publication set the foundation for future work which allowed focus on risk as a major component to developing a unified framework. Below is the paper with accompanying diagrams and figures.

Unified Approach to Sustainability, Resiliency and Risk Assessments of a Tailings Dam

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Abstract

Generally, researchers consider sustainability and resiliency aspects of infrastructure projects independently, without considering the relationship that exists between them. Unified approaches that combine sustainability, resiliency, and analyze risk are very minimal. This paper proposes a unified approach to assessing sustainability, resiliency, and risk for infrastructure via evaluating the performance of a tailings dam under various earthquake magnitudes. A tailings dam is typically in operation for many years, which means they may have a direct impact on the local environment, society, and economy. Due to the extended life of the dam, the probability of a major event occurring that could negatively impact the durability of the dam increases. Hence, it is important to study impacts on the environment and economy under regular (sustainability analysis) and extreme (resiliency analysis) conditions in conjunction with their probabilities of occurrence. This paper studies the interrelationships between sustainability, resiliency and the potential risks of a negative impact upon infrastructure. Results provided show that a unified approach with emphasis on risk offers a more holistic, and accurate depiction of a system's overall quality.

Keywords: Sustainability, Resiliency, Risk, Unified Approach, Tailings Dam

Introduction

In consideration of the potential hazard to the world's ecology, researchers and engineers have begun discussing methods to asses and design civil infrastructure with considerations of sustainability and resiliency. Sustainability is defined by the American Society of Civil Engineers, as "a set of environmental, economic, and social conditions - the "Triple Bottom Line"- in which all of the systems have 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). Resiliency is commonly identified as a system that undergoes a loss in functionality due to an event that has low probability but high impact, and that system is regaining functionality within a specified time. For a system or project to be considered resilient, it must meet criteria outlined by four pillars of resiliency; robustness, resourcefulness, rapidity, and redundancy (Bruneau and Reinhorn 2006). Further, the definition of resiliency includes a probabilistic assessment of the system. The probability of an event that could impact the functionality of a system, and the probability of impact on functionality due to that significant event, is resiliency as outlined by Chang and Shinozuka (2004).

Numerous researchers (Basu et al. 2015; Haeri 2016; Lee 2016) have outlined procedures to perform sustainability and resiliency assessments separately in a mutually exclusive fashion, while few have measured the effectiveness of unifying these assessments. Bocchini et al. (2014) identified the inefficiencies in considering sustainability and resiliency impacts separately mainly because of the vast number of similarities and common characteristics between the two. For example, both analyses require life cycle assessments to study the impacts and both analyses study the impact of the infrastructure through impacts on economy, environment and society. Hence, Bocchini et al. (2014) outlined a unified approach to sustainability and resiliency assessments for various civil infrastructure. Researchers also made special note that risk theory should be incorporated into the assessments in order to have systematic unification of resiliency and sustainability. This is largely due to the close relationship risk has with the concept of resiliency, and the interconnectedness of sustainability and resiliency. Also, if the risk is neglected there is an increased potential for designing infrastructure that may be inadequate or susceptible to failure. Accounting for risk allows decision makers to properly identify design alternatives that may best suit their needs, while ensuring the design meets sustainable and resilient parameters. Proposed here is a unified approach that uses the concepts of the probability of occurrence and risk in order to address the resilience and sustainability of the civil infrastructure simultaneously and quantitatively. The potential benefits of a unified approach for sustainability, resiliency, and risk are outlined using a model of a theoretical tailings dam. The analysis performed for this paper is divided into two sections; individual sustainability and resiliency assessments, and unified sustainability, resiliency, and risk assessments. An example of a proposed tailings dam is provided to show the added benefit of including risk into the unified approach by comparing the results from the discrete and unified approaches.

Lèbre and Corder (2015) mentioned that sustainability and resilient concepts are interlinked for mining operations, as a mine cannot be sustainable if it is not resilient enough to stay in operation for the entire life cycle of the mine. In the event of closure, waste material is either left without proper rehabilitation or mitigation, which may reduce the functionality of the tailings dam, and decrease the sustainability (Lèbre and Corder 2015). Considerations for risk concepts are outlined in work on risk analysis performed by Baecher and Christian (2000), as they identified the total amount of dams in the United States are over 75,000 and the average dam failure rate is approximately 7.5 dams per year. This shows that dams currently hold a high risk for failure, and efforts to mitigate these failures are needed within the mining industry.

Tailings Dam Analyses

A potential mine located in southwest Idaho will be mining molybdenum and copper deposits and will require a tailings dam to store waste material from the mine. Due to the quantity of valuable material, this project has the potential to have significant environmental, social, and economic impacts in the Boise area. By industry standards, tailings dams are typically constructed to be impervious, earthen dams, which grow in height as the mine grows in depth (Davies et al. 2002). Prior to any material or slurry being contained by the tailings dam, a starter dam must be constructed (Hamade 2013). A starter dam is a critical aspect of a tailings dam and the stability of this dam is crucial to the overall stability of the tailings dam. Earlier analyses performed by Robbins and Chittoori (2017) showed that this starter dam should have a slope of 2.5 horizontal to 1 vertical and a height of 15 m while the overall height of the tailings dam was needed to be 250 m to ensure the reservoir was large enough to contain all the projected waste material produced from the mine.

From work performed by Robbins and Chittoori (2017), the tailings dam was shown to be safe against an earthquake of magnitude 5.5, although it could be argued that the dam needs to be safe against higher magnitude earthquakes. This would alter the geometry of the starter dam and as a result alter the geometry of the overall tailings dam. This change would have impacts on the sustainability of the entire mining operation. Hence, it is important to study the dam under various magnitude earthquakes along with the likelihood of their occurrence. In order to study this in detail, the starter dam was subjected to five different magnitudes of earthquakes ranging from 5 to 7 and the probability of failure under each of these magnitudes was recorded. Further, the slope of the starter dam was altered from 2:1 to 3.5:1 to study which of these slopes would be safe under the different magnitude earthquakes. After this information was established, separate sustainability and resiliency assessments in the form of cost to construct and cost to recover were analyzed for each case. Finally, a unified approach to sustainability and resiliency assessments including risk theory was used to study each of the slopes and earthquake magnitudes. The following sections detail each of these analyses along with the results and discussion.

Numerical Model of the Starter Dam

Figure 1 shows the numerical model of the starter dam with a slope of 2.5 horizontal to 1 vertical and a height of 15 m. The internal geometry of the starter dam consists of a porous layer, located vertically along the centerline of the dam and horizontally across the downstream slope at the base of the dam to direct fluid flow and lower the phreatic surface. A geotextile was utilized next to the porous layer to prevent internal erosion, piping, or liquefaction caused by fluid flows exceeding maximum allowable velocities. It was assumed that the starter dam would be constructed using the waste from mining operations. Since these materials were not tested, the material properties were obtained from the literature for waste material produced by the similar mine. Values obtained from the literature (Bhanbhro 2014; Holmqvist and Gunnteg 2014; Hu et al. 2016) were used as the upper and lower limits for computational analysis. It was assumed that the properties were normally distributed between these upper and lower limits. The purpose of using researched data was to design the dam using materials that have been tested and their mechanical properties verified, which ensures that the results are ‘realistic’. Assigning a distribution to the given values allowed for a statistical variance to be modeled within the software given variation in actual material properties. Various types of distributions are available for analysis, however for simplification a normal distribution was used for this analysis. Values obtained from research such as void ratio, unit weight, friction angle and hydraulic conductivity are shown in Table 1.

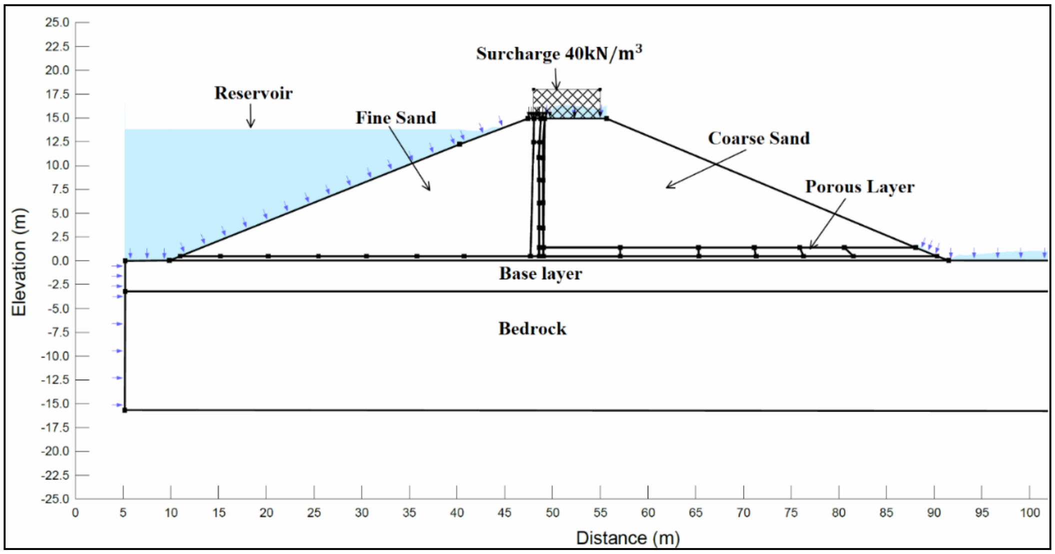


Figure 2: Tailings dam model layout, and dimensions

Table 1: Geotechnical Properties of Soil Used for Construction of Tailings Dam

Soil	Unit Weight (kN/m^3)	Hydraulic conductivity $^{m}/_{s}$	φ'	Poisson's Ratio	Damping Ratio	e
Course Sand	23.5	1.1E-01	42	0.45	0.1	0.84
Fine Sand	17.7	5.7E-05	32	0.33	0.3	0.99

Evaluation of the starter dam stability was performed by analyzing seepage, slope stability, and earthquake resilience by use of numerical software GeoStudio (GEO-SLOPE International Ltd 2016). Seepage was analyzed to ensure internal erosion, or liquefaction does not occur within the dam due to seepage velocity exceeding the maximum. An assumption was made that the viscosity of the liquid flowing through the dam was equal to water to model the worst-case scenario. Maximum allowable seepage velocity was assumed to be 4 cm/s, as suggested by Richards (2012).

Slope stability was analyzed using Bishop’s method of slices. Material properties for the soil were assumed from published data by Bhanbhro (2014), Hamade (2013), and Wang et al. (2015). Variation in material properties was accounted for by use of Monte

Carlo simulations. Material density values were normally distributed between known maximum and minimums and assigned a standard deviation of 0.5 to account for variation in the engineered particles. Monte Carlo simulations varied the material properties to determine which were the most probable, and those most probable were then used to determine a Factor of Safety (FS). For each simulation, slope stability calculations were performed by Bishop's method of slices, and finite element analysis within the previously mentioned software. From this analysis a Probability Density Function (PDF) was produced, and the mean value provided within the PDF was used as the most probable FS.

Sustainability Assessments

In this study, sustainability assessments were conducted considering only economic and environmental aspects. The economic aspects include the economic viability i.e. cost benefit comparisons whereas environmental aspects include the calculation of Embodied Energy (EE), and Embodied Carbon (EC). Measuring EE and EC shows how much energy was consumed and how much carbon was produced in constructing the project, which can be directly correlated to environmental impact. An additional method used for assessing the sustainability of the dam was a modified Life-Cycle Cost Analysis (LCCA). For the purpose of this analysis, the LCCA was computed by analyzing cost directly associated with the construction and rehabilitation of the tailings dam. A generalized assumption was made that any costs associated with the operation of the mine were essentially similar for all scenarios, and able to be neglected for this analysis.

Discrete sustainability was measured by considering the economic and environmental impacts. Economic impact was based on a cost of construction for the tailings dam (Mosquito et al. 2015). An assumption was made that regardless of any action taken on the tailings dam, all social impacts would all be relatively similar between the different slopes of the starter dam. Social aspects were neglected during this analysis, however for the proposed framework social analysis should be considered and done by methods similar to guidelines outlined in work by Valdes-vasquez et al. (2013). For environmental impact, a tailing dam's model - using minimum dimension/slope requirement as per state law, was analyzed for safety against seepage and slope stability using the software without considering seismic activity. A series of static simulations were executed to establish the smallest dimensions possible that would satisfy minimum requirements. The computations on embodied energy, and embodied carbon for that dimension were computed using the Institution of Civil Engineers (ICE) database (Circular Ecology 2016).

Results from the sustainability computations show that the most cost-effective construction method was to build the tailings dam with a 2:1 slope. This is due to the 2:1 sloped dam having to use fewer materials in construction which directly relates to environmental, and economic costs, as shown in Table 2.

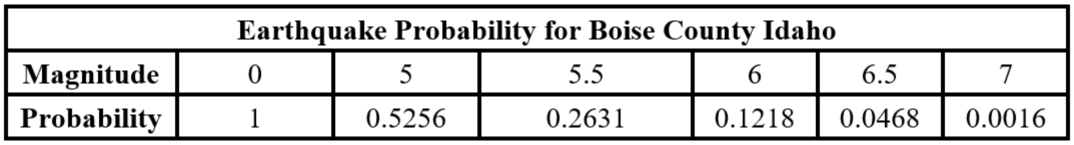
Table 2: Results from Sustainability analysis

Slope (H:V)	EE (MJ)	EC ($kgCO_2$)	Cost (millions)
2:1	3.60E+10	2.08E+09	$305
2.5:1	4.48E+10	2.59E+09	$380
3:1	5.36E+10	3.10E+09	$454
3.5:1	6.23E+10	3.61E+09	$529

Resiliency Assessments

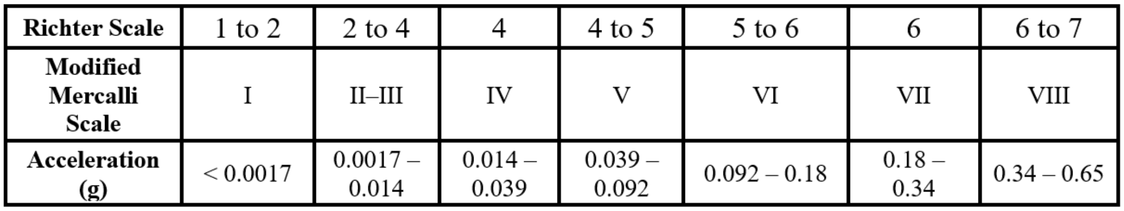
The definition of resiliency in this work is determined on the robustness of the tailings dam. Robustness of the tailings dam is based on functionality, which is representative of slope stability. For quantifying robustness, the tailings dam analyzed for its seismic performance in terms of the computed FS. Slope stability was evaluated for both static analysis and seismic analysis. The probability of occurrence was used as a component within the seismic analysis. Given the location of the proposed tailings dam, the probability of being impacted by an earthquake ranges from approximately 50% for a magnitude 5, to 0.16% for a magnitude 7, as shown in Table 3. The PHA was used by the software to simulate the earthquake of varying magnitude. Linking PHA to a magnitude of the earthquake was determined by comparing PHA to the Modified Mercalli scale, then comparing the Modified Mercalli scale to the Richter scale (Robinson 2013; USGS 2017), as shown in Table 4.

Table 3: Earthquake probabilities for Boise County Idaho



Earthquake Probability for Boise County Idaho						
Magnitude	0	5	5.5	6	6.5	7
Probability	1	0.5256	0.2631	0.1218	0.0468	0.0016

Table 4: Correlation between PHA, Modified Mercalli scale, and Richter scale



Richter Scale	1 to 2	2 to 4	4	4 to 5	5 to 6	6	6 to 7
Modified Mercalli Scale	I	II–III	IV	V	VI	VII	VIII
Acceleration (g)	< 0.0017	0.0017 – 0.014	0.014 – 0.039	0.039 – 0.092	0.092 – 0.18	0.18 – 0.34	0.34 – 0.65

Several analyses for seepage, slope stability and seismic stability were done using software and FS for each PHA. Any FS greater than or equal to 2.0 is considered 100% functionality, and any FS less than or equal to 1.0 represents a catastrophic failure, or 0%

functionality. A correlation between PHA, tailings dam dimension and FS was then established. This methodology allowed for the evaluation of FS based on probabilistic analysis, such that a computed FS was then determined as a probability of failure, given the occurrence of an earthquake.

Results from the resiliency assessments show that to maintain functionality in the event of an earthquake, the tailings dam should be constructed with a wide base. For earthquakes that are magnitude 5 or less, the slope of the tailings dam may be as steep as 2:1. Magnitude 6 earthquakes require slopes of 3:1, while magnitude 7 may require a tailings dam slope of 3.5:1, as shown in Figure 2.

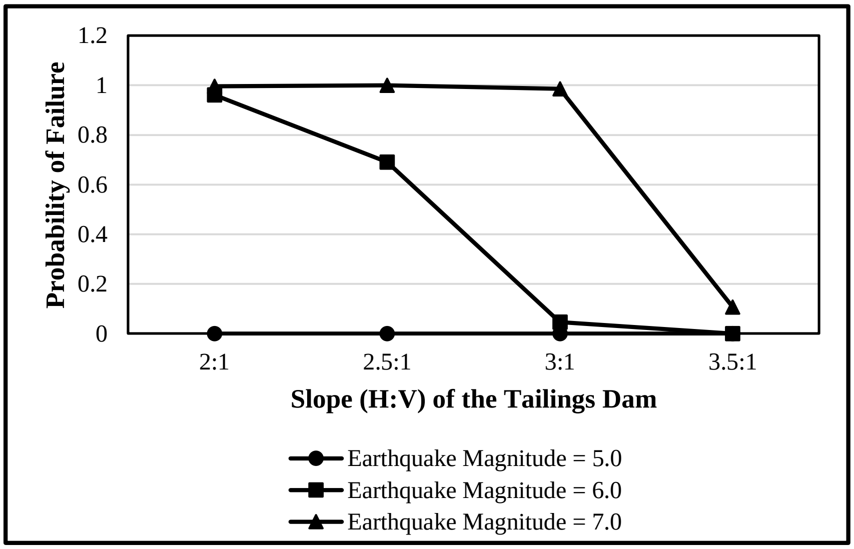


Figure 3: Graph of the probability of failure vs tailings dam slope.

Unified Approach to Sustainability, Resiliency, and Risk

When evaluating for sustainability, the example shows that the most sustainable option for the tailings dam was to construct the dam with a slope of 2:1, which is the minimum required slope allowable for the state of Idaho. The sustainability analysis neglected the potential for an earthquake, and how the earthquake could impact the functionality of the tailings dam. Evaluation of resiliency for the example provided guidance for decision makers to construct a tailings dam that could sustain function from a low probable, but high impact event. This method shows a tailings dam constructed with the maximum width of a base analyzed and proved to be more resilient than any other. However, the discrete resiliency analysis neglected the economic and environmental impacts that would occur from constructing a highly resilient, robust dam.

To mitigate the issue of neglecting key aspects to developing civil infrastructure when performing a discrete analysis for either sustainability or resiliency, this paper proposes unifying the two assessment methods. In addition to assessing sustainability and resiliency, the use of risk as another aspect of the system's analysis to aid in quantifying the overall quality of the system, as shown in Figure 3. The unified approach to measure sustainability and resiliency is a modified form of frameworks from Das et al. (2016), Bocchini et al. (2014) and Chang and Shinozuka (2004).

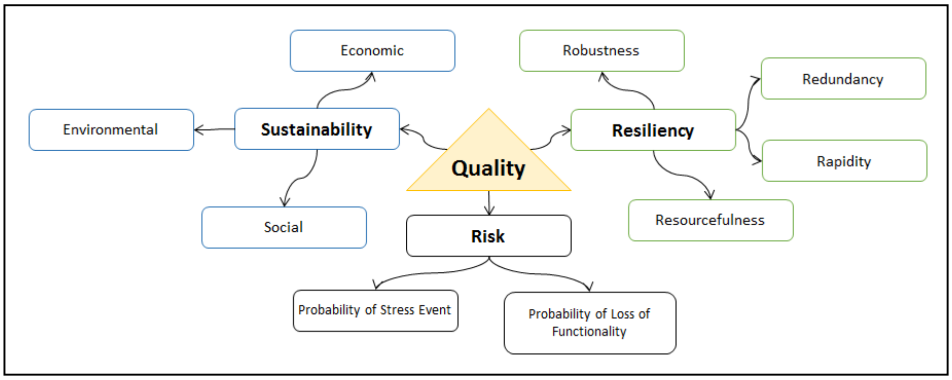


Figure 4: Flow chart for aspects that make up the total quality of a system

Procedural steps to implement the unified approach to assessing sustainability and resiliency with risk are intentionally short, concise, and relatively simple to perform. This simplicity allows for easy implementation within any aspect of civil infrastructure design. Step by step procedures are as follows;

1) When considering a design alternative, perform a cost analysis for all possible designs. The cost analysis could be for an entire life cycle, or just the initial costs.
2) Verify how the performance may be affected under various possible extreme events. Here uses the probability of occurrence of each event, as well as measure the potential impact that event may have on the function of the infrastructure.
3) Use Bayes' Theorem to determine which extreme events are most likely to cause failure.
4) Estimate the cost of repair needed due to the occurrence of the extreme event and express the cost as a function of the probability of failure.
5) Combine costs from the first step with the repair costs along with their probabilities of occurrence and compare alternatives.

This proposed framework may be used to assist decision makers in determining the most effective design methods to support sustainability and resiliency.

Discussion

For the example provided in this paper, the tailings dam results for both the discrete sustainability and resiliency analysis suggested two opposing design methods. For the sustainability analysis, the tailings dam is recommended to be constructed by using the minimum state standards for slopes of 2:1. For the resiliency analysis, the results suggested constructing the tailings dam to have a wide, flat slope of 3.5:1 to sustain from high impact earthquakes.

Unifying the analysis for sustainability and resiliency coupled with risk allowed for examination of which design alternative had the highest probability of failure given the occurrence of an earthquake. This was then monetarized to allow for sustainable assessment of the tailings dam. Costs were normalized to the minimum cost of construction for the tailings dam. From the seismic analysis, the probability of failure was computed, and then used with the probability of occurrences for a given magnitude of earthquake. These results were then used in the Bayes' Theorem computations to determine the probability that a certain magnitude of earthquake caused a failure, given that a failure occurred. Each computed FS was determined based on the variation in material properties provided by Monte Carlo simulations. The simulations were performed via software, and the results obtained were plotted as a probability of failure vs. FS graph. Using the mean value of the probability of failure, a respective FS was then determined. This allowed for a relationship to be made on what magnitude of earthquake, caused a failure for a given slope. Bayes' Theorem was performed by collecting the known probabilities of certain magnitudes of earthquakes in the area where the dam is located. Then computing the probability of failure given the occurrence of each magnitude of earthquake, and each slope design of the dam. From this, the probability of failure given that a certain magnitude of earthquake occurs was computed.

From the results, the most probable failures were determined to be magnitude 6 earthquakes, on a 2:1 and 2.5:1 slope ratio, a magnitude 6.5 on a 3:1 slope, and a magnitude 7 for a 3.5:1 slope, as shown in Table 5.

Table 5: Results of probability of failure by use of Bayes' Theorem

Bayes' Theorem				
PoF	**Magnitude**			
slope (H:V)	**5**	**6**	**6.5**	**7**
2:1	0.00	0.71	0.28	0.01
2.5:1	0.00	0.63	0.35	0.01
3:1	0.00	0.11	0.87	0.03
3.5:1	0.00	0.00	0.00	1.00

Cost of repair was assumed to be the percent of functionality lost, multiplied to the construction cost. Cost of repair added to the initial costs without the consideration for risk showed that the lowest average cost total was the tailing dam with a 3.5:1 slope, as shown in Figure 4. When incorporating risk into the unified approach, the total cost was shown to be the lowest for the tailings dam with a 2:1 slope, as shown in Figure 5.

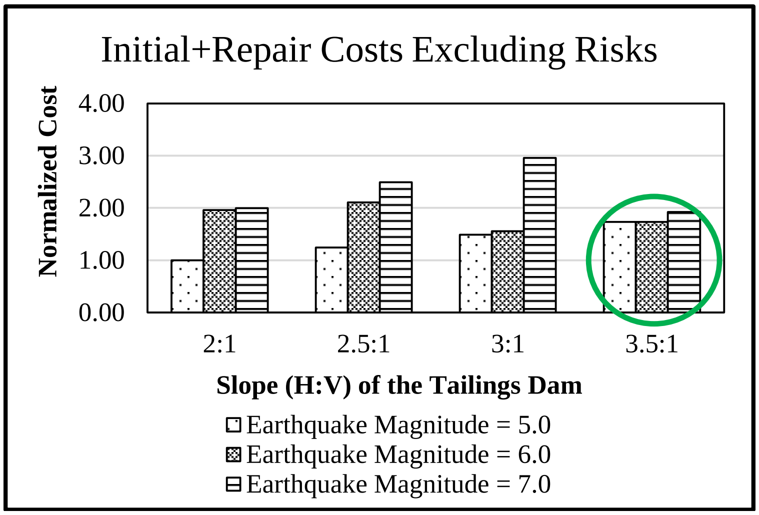


Figure 5: Total cost comparison without consideration of risk

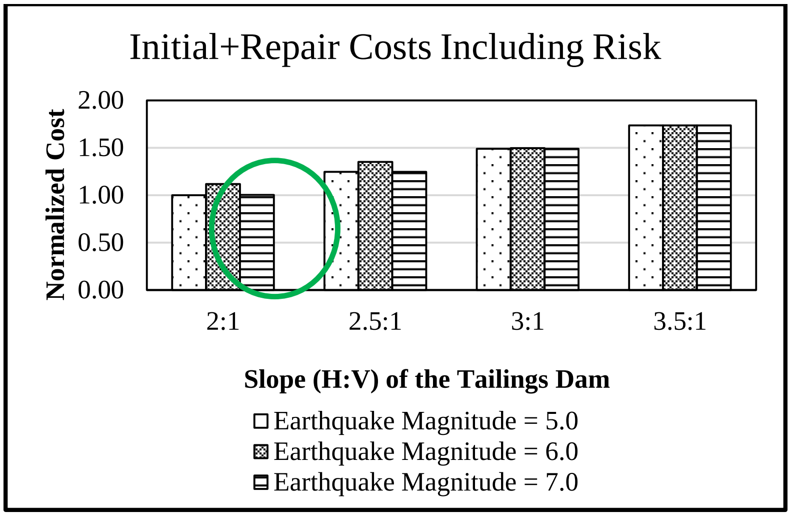


Figure 6: Total cost comparison considering risk

Comparison between the analysis with, and without incorporation of risk shows that the actual cost of the tailings dam may actually be much less than what is shown by only using the discrete methods, and not incorporating risk.

Summary and Conclusion

As proposed in this paper, the framework to assess sustainability, resiliency and risk has been outlined. This framework has the potential to assist decision makers in being able to come up with an effective design that balances the requirements to make the design both sustainable and resilient, by use of analyzing risks of potential hazards. This framework may be utilized for any type of infrastructure, if the proper life cycle costs are known, as well as potential hazards and probabilities of occurrence of those hazards. The example provided in this work showed a basic conceptual method to utilize the framework but neglected several factors that may be necessary to perform the analysis for actual consideration of alternative designs. Suggested methodologies, along with basic steps of analysis were the goal of this paper, along with providing a simple, yet effective framework that uses risk as a key component into the decision-making process for designing for sustainable and resilient infrastructure. Further work may include developing a systematic process that incorporates all aspects of sustainability and resiliency to obtain a more holistic assessment of a design alternative.

CHAPTER THREE: DETAILED WORK ON UNIFIED FRAMEWORK

A journal publication was produced to convey explicit details of how to unify resiliency and sustainability. Within this journal paper, each step was covered, as well as the methods and meaning behind the risk-based approach to unifying Sustainability and Resiliency (S&R). When developing this approach, the Bayesian method, which was previously researched by other authors was expanded on by developing a risk-based approach for both resiliency computations as well as sustainability. These additions made the framework more applicable, as the changes in the system's ability to rebound, or withstand negative impact directly affect the system's sustainability rating. Below is the text of the journal publication.

A practical risk-based, probabilistic method to unify 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. This is evident in the development of frameworks to assess sustainability or the resiliency of civil infrastructure. Researchers have developed discrete methods to quantify the sustainability of a certain system, while some researchers have developed discrete methods to quantify the resilience of civil infrastructure. Even fewer researchers have attempted to unify the sustainability concept with resiliency, and the ones that have tend to make the unification process complex and overly specialized which in turn leaves their methods seldom used, or purely theoretical. Proposed here is a framework to mitigate the issue of overly complex and unusable frameworks for assessing the sustainability and resiliency of civil infrastructure. Outlined within this paper are explicit steps, methods to use the framework, as well as an example of infrastructure that shows more than one type of failure mode.

Keywords are chosen from ICE Publishing list

Infrastructure planning; Sustainability; Risk & probability analysis

Introduction

As of spring 2019, numerous cities, agencies, firms and universities are focused on developing infrastructure that is both sustainable and resilient to failure. Balancing the needs to build robust, and resilient infrastructure with the focus on sustainable development requires a probabilistic approach. The probabilistic approach can be assumed to be the risk of occurrence for a catastrophic event, paired with the probability of failure given the occurrence of a specific event. 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 discretely assess the sustainability or resiliency of infrastructure. 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 that is capable of assessing the Sustainability and Resiliency (S&R) of civil infrastructure based on the risk of a catastrophic event, this paper proposes a simplistic, 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. With the development of this framework, practitioners may be able to employ methods to assess the overall quality of their design, which will inevitably lead to a more resilient, and sustainable built environment.

Sustainability

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” – 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 and equilibrium between each pillar, the higher the overall quality of the system, as shown in Figure 6.

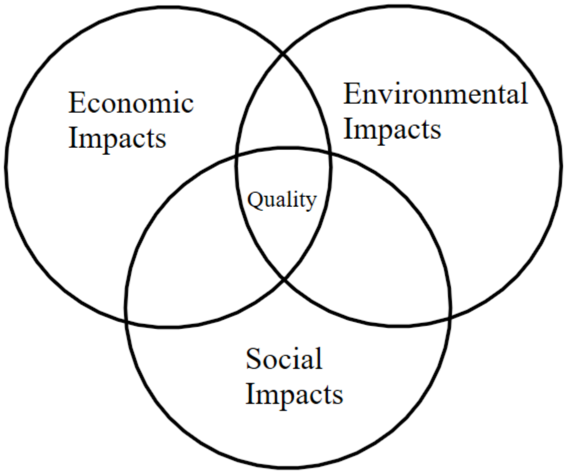

Figure 7: Vienne Diagram of relationships of the overall quality of a system

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.

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. 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.

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, ($PM_{2.5}$/PM_{10}, NO_X, CO, SO_2), 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.

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).

In addition to the previously mentioned 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 all employ individual assessment methods for both sustainability and resiliency.

Drawbacks to 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.

Resiliency

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 to identify, obtain, and use material and/or other assets to perform the rehabilitation efforts after an event. Rapidity is the time from the occurrence of the catastrophic event to the completion of the rehabilitation efforts. Redundancy accounts for additional systems, components or assets that can perform the same function of the original asset.

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, Reinhorn and Bruneau, (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). As stated by Lee & Basu (2017), Drivers are the forces that motivate social actions, or the pursuit of vital needs such as food, water and shelter. Pressures are threats or potential hazards civil infrastructure may encounter, such as earthquakes, hurricanes or floods. 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 rehabilitate the infrastructure after a catastrophic event. The DPSIR assessment is evident in most resiliency frameworks and can be adaptable to almost any infrastructure.

Drawbacks to Resiliency Frameworks

Discrete methods of assessing the resiliency of civil infrastructure have been developed by several researchers, and generally for very specific systems. This allows for explicit analysis of specific types of infrastructure but prevents utilization of these frameworks on other systems. 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. Also, Das et al. (2016) used the slope stability of an earthen dam to determine the robustness of the dam. Other discrete frameworks exist but will not be mentioned here. 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 assessments by analysing several bridges. The framework Bocchini *et al.*, (2014) developed inherently neglected risk, or any form of probabilistic analysis. There are, however, several frameworks that account for risk. Risk based frameworks are typically specific to a certain type of infrastructure or investigate only one type of failure. Further, risk based approaches 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).

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. If risk is neglected there is an increased potential for designing infrastructure that may be inadequate or susceptible to failure, which is neither sustainable nor resilient. 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 the product of the frequency of an event, the probability of occurrence, and the 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. 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).

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 simplistic 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. Similarly 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 of 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. Further, the proposed framework is to develop a unified approach that is applicable to geotechnical engineering and is readily usable by engineers and practitioners. With that in mind 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, Figures 7 and 8.

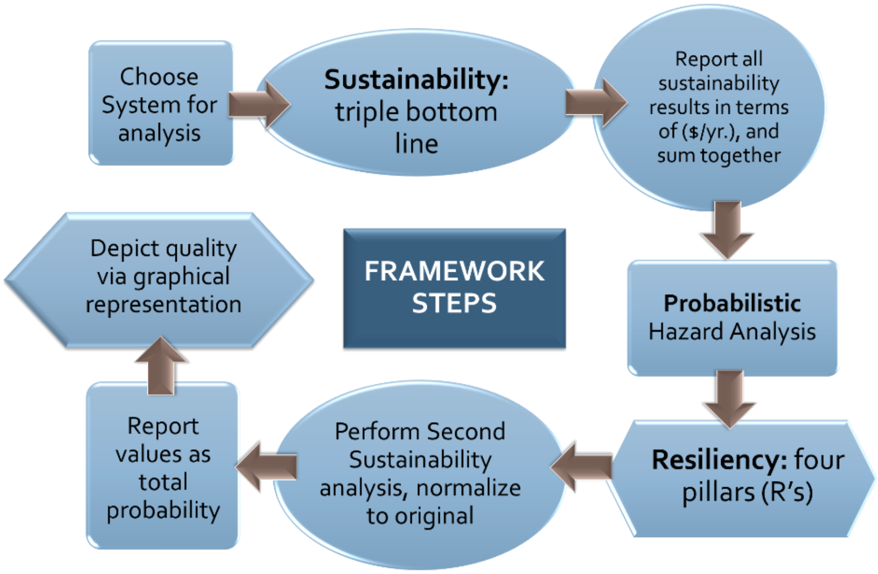

Figure 8: **Flow chart depicting the method of analysis for S&R framework**

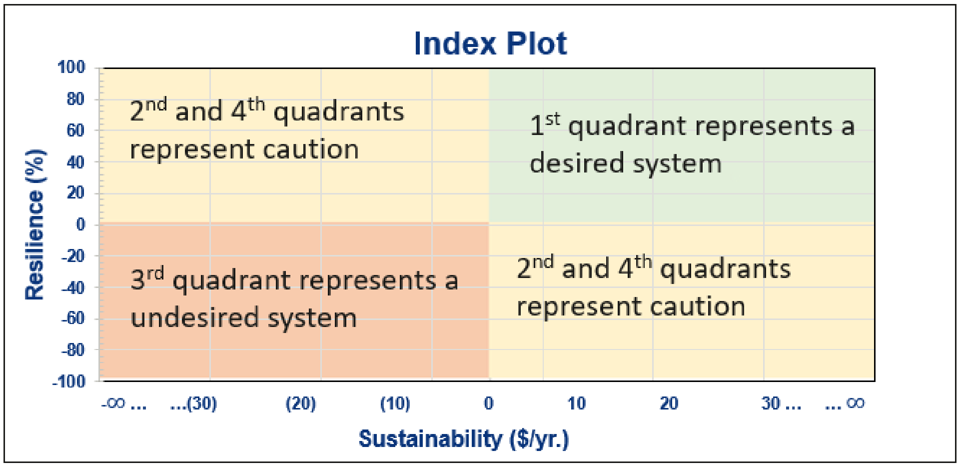

Figure 9: Graphical representation of S&R assessment results.

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, an earthen dam near Boise, Idaho was analysed.

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 1,000 ft. at the crest, and reaches a maximum height of 350 ft. 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 307,000 acre-ft. 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.

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. 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 course 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 9. 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 6.

Table 6: Lucky Peak material Properties, obtained from USACE

	Clay Layer		**Random Layer**		**Shell Layer**	
	Design	**Used**	**Design**	**Used**	**Design**	**Used**
Internal Friction Angle (φ')	30	29-31	37	35-37	33-35	40
Unit Weight (Moist) (lb/ft^3)	130	124	125	127	125	130
Unit Weight (Sat.) (lb/ft^3)	135	130	135	135	140	135

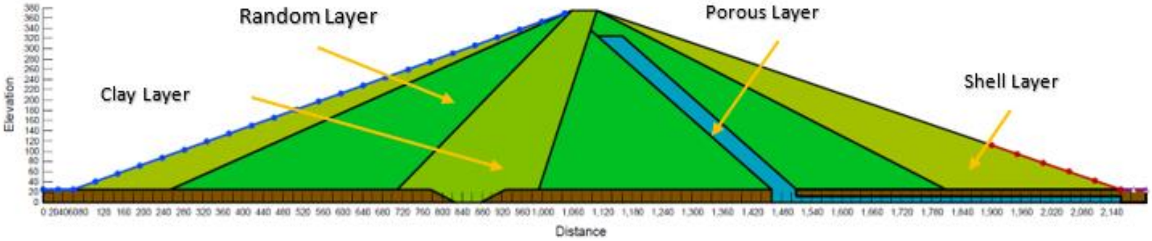

Figure 10: Model of Lucky Peak, showing internal geometry

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. For all models, slope stability was calculated by use of the Bishop’s method of slices, as outlined by 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. 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, 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.

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.).

Environmental Impacts

Although there are numerous impacts available as a metric 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) 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

$$\left[\frac{lbs}{hr}\right]_i = \left[\frac{g}{bhp-hr}\right]_i \times bhp_{\max} \times \frac{1lb}{454g} \qquad (1)$$

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 (Table 7). An estimated 921,000 people per year use the recreational services of Lucky Peak, at a fee of $5.00 per car load and the average registration cost of $30.00 per 12 ft. 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 $4,600.00 per acre (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.

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.

$$FV=PW(Cost, Interest\ Rate, Design\ Life) \tag{2}$$

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.

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

$$P(A|B) = \frac{P(B|A)P(A)}{P(B)} \tag{3}$$

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.

Table 7: Earthquake Probability of occurrence and change of FS table

Hazard	Earthquake				
Magnitude	5	5.5	6	6.5	7
Probability	0.5256	0.2631	0.1218	0.0468	0.0016
Factor of Safety	1.438	1.438	1.059	0.949	0.959
% change in FS	0.10125	0.10125	0.338125	0.406875	0.400625

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 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 water is removed, the dissipation of pore-water pressure is highly influenced by the permeability and material properties of the soil. 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 for 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 8.

Table 8: Flooding events with corresponding changes in FS given rapid drawdown

Hazard	Flooding event					
Discharge (cfs)	6000	10000	20000	30000	35000	40000
Probability	1	0.5	0.32	0.1	0.035	0.002
Factor of Safety	1.08	0.999	0.592	0.251	0.198	0.115
Slip surface failure area (ft^2)	0	5000.2	9063	29428	32561	56731

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. It was assumed that the required material for rehabilitation was equal to that of the failure circle shown in the model, as shown in Figure 10. 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 could be 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.

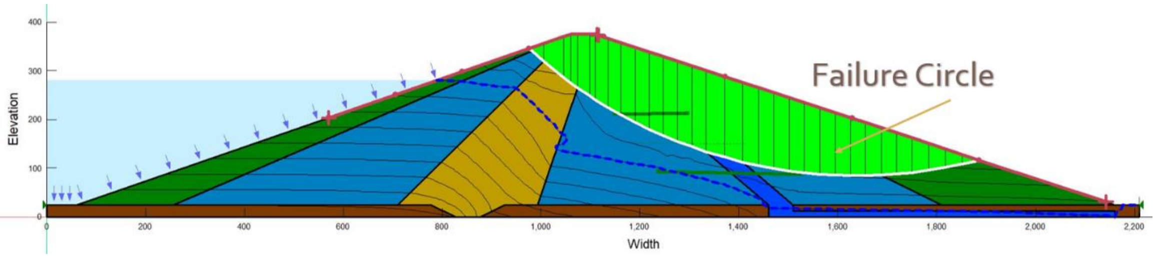

Figure 11: Slope analysis, slip circle failure plane

Equation 4: Resources equation

$$Available\ budget = \frac{(supply - demand)}{demand} \qquad (4)$$

Rapidity

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.

Sustainability Impact Following Catastrophic Event

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 neglected, as they are already accounted for in the 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.

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.

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.

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 7. The overall index was summed to be $41,165,000 per year.

Table 9: Sustainability results

Environmental impact ($/yr.)	**Economic impact ($/yr.)**	**Social Impact ($/yr.)**
-$ 354,000	-$ 9,200,000	$ 51,000,000
Fuel Burned (gal/yr.)	**Total Mbtu/yr.**	**Total CO (tons/yr.)**
260,000	21,800	43

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 maybe the difference in results from the seismic analysis, to the rapid drawdown was 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.

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. Figures 10 and 11 show the graphical results from the analysis of seismic and rapid drawdown of Lucky Peak.

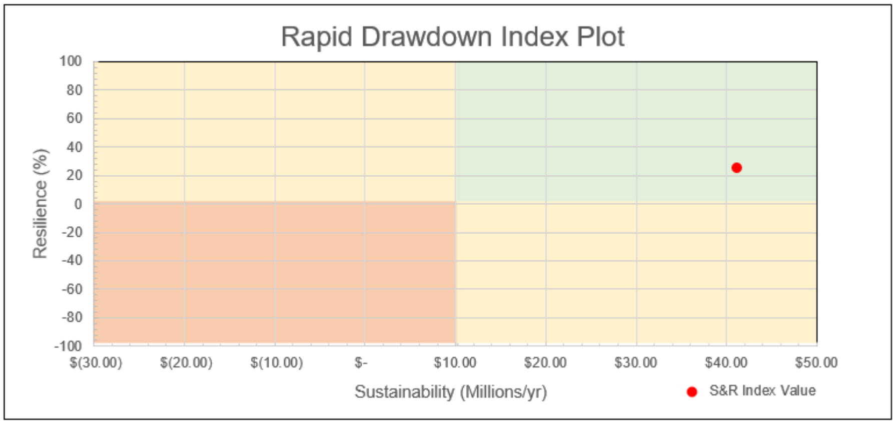

Figure 12: Graphical representation of rapid drawdown results

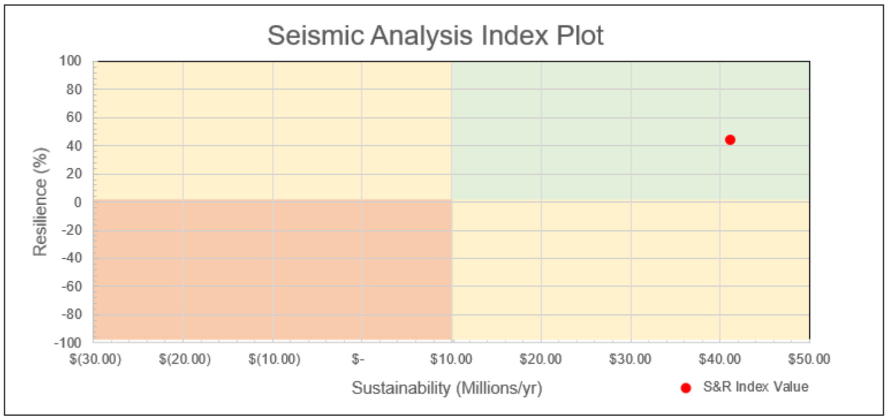

Figure 13: **Graphical representation of seismic analysis results**

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 as to how the framework can be deployed on civil infrastructure. Discussion of some of the assumptions made to complete this work, the main points about the framework and relevancy are all covered in the following paragraphs.

Novel aspects of this framework revolve around the simplicity, and flexibility of the framework. Major input parameters are use 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 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.

CHAPTER FOUR: SUMMARY AND CONCLUSION

Summary

The main purpose of this thesis is to provide a framework that is practical, and realistic such that current engineers and policy makers are able to obtain this framework to assess the sustainability and resiliency of civil infrastructure. The introduction that was given in chapter one outlines that there is a need to develop a method to jointly assess sustainability and resiliency of civil infrastructure, while considering the risk of failure given the occurrence of a catastrophic event. Also outlined within chapter one is a basic format of research methods on how this thesis was developed, and how the framework was crafted to meet the objectives of the thesis. Chapter two covers the formulation of the basic idea for the framework, such that the basic concept is covered and presented in a way that lays the foundation for the work. With understanding how the main components fit together, while formulating a Bayesian approach to assess risk, both sustainability and resiliency were generally unified, and the basic framework took shape. Chapter three covers the bulk of the details for the framework as it outlines the required material for a journal publication. The journal publication explicitly covers the methods and computations that are required for all the inputs needed to compute both the sustainability and resiliency indices. Each input value is then directly correlated to the output and the results are graphically represented such that the user is able to quickly identify the assessed quality of the system. To compute the S&R assessment, chapter three explicitly covers two examples that show the methods and outcomes of using the framework. Each example covers a different scenario that could potentially occur at the location of Lucky Peak dam, with associated probabilities and potential failure outcomes. Finally, chapter three covers assumptions, potential improvements, and relevance of the framework.

Conclusions

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 thesis discussed the basic overview, methods and concepts that are required to utilize this framework as well as provide an example as to how the framework can be deployed on civil infrastructure. Discussion of some of the assumptions made to complete this work, the main points about the framework and relevancy are all covered in the following paragraphs.

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 variables 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 a feasibility study or even used another S&R assessment, 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.

Considering that the output is in fact user defined, a potential issue with the use of this framework is the replicability of output given multiple failure mode analyses. General input values are expected to be used, as most design scenarios do not know explicitly every minute detail associated with that system. When general values are used, the outcome is then a general outcome that may lack the accuracy to the actual outcome. Representation of the results is provided as a point on a cartesian coordinates system, which does not allow for the potential range of values that could occur given changes in ranged values, or inputs. This then means that the results have to be presented as discrete values, and in order to provide a varied result with a distribution, input values have to be changed over the possible range of values determine the sensitivity of the results.

Without the exact data on how a dam is constructed, the internal geometry, social impacts or the total property worth saved from flooding by the existence of the dam, many assumptions 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 a direct component of the Lucky Peak dam itself but is an overall component to the general 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.

Future Research

Resiliency computations are predominantly dependent on changes in functionality over time after the occurrence of a catastrophic impact. Methods to determine this change in functionality could be as varied as each user who performs the analysis may have a preferential method in modelling software or failure mode analysis. Irrespective of the chosen method of analysis, almost any simulation could be used so long as both the change in functionality, 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. Future research may use alternative modelling methods to determine accuracy between approaches.

To mitigate the variability of results, determining the actual input values that would be used for the construction of a type of infrastructure would greatly assist the accuracy of the S&R assessment. With the use of general values, the results are still variable based on user input. This prevents the framework from having accuracy, or legitimacy in the assessment of an actual system.

As this analysis was performed solely on an earthen dam, further development of the framework could consist of expanding the applicability beyond geotechnical systems. As the basis of this thesis was to create an S&R framework explicitly for geotechnical systems, to truly test the robustness of the framework, application to additional systems must be performed.

Primary focus on this thesis 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 was shown through example, and is acceptable for now, but future work may push to unify the indices into one index. This could produce a more accurate representation of the quality of the system analysed, as it will explicitly unify the results into one value. Also, the use of a single output value would be beneficial when considering the occurrence of multiple hazards that could cause failure. This could be performed by developing one single output value to assess the quality of the infrastructure, then potentially use that value as a weighted multiplier with several other hazard analyses to gain a weighted index which identifies the quality of the system given the occurrence of numerous hazard events.

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. There are several considerations that need to be addressed prior to the framework being instilled as a method for use on infrastructure beyond that of geotechnical systems, but the development of this initial work allows for the research to continue and expand the use of the framework as needed. Coverage of the strengths, weaknesses and potential for the use of this framework was detailed throughout this thesis.

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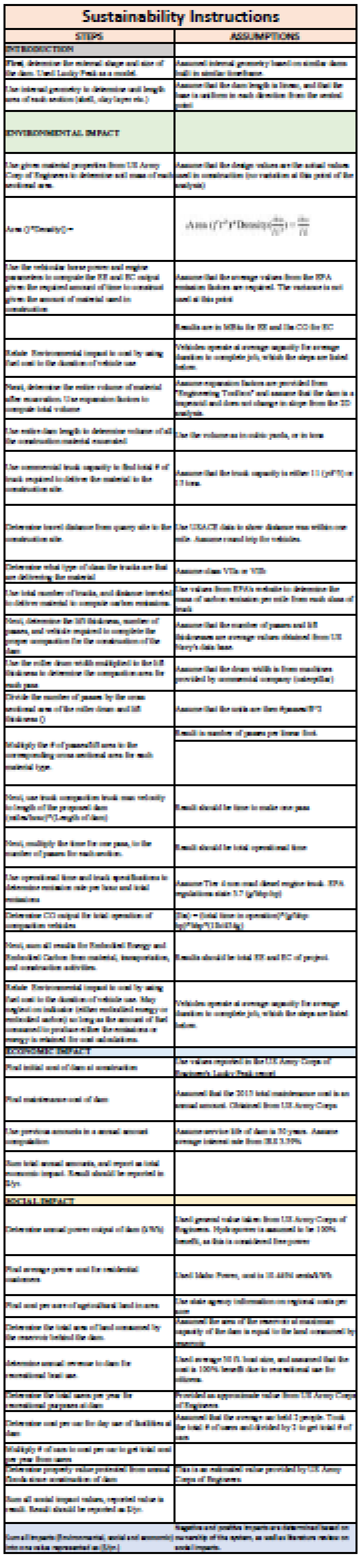
APPENDIX A

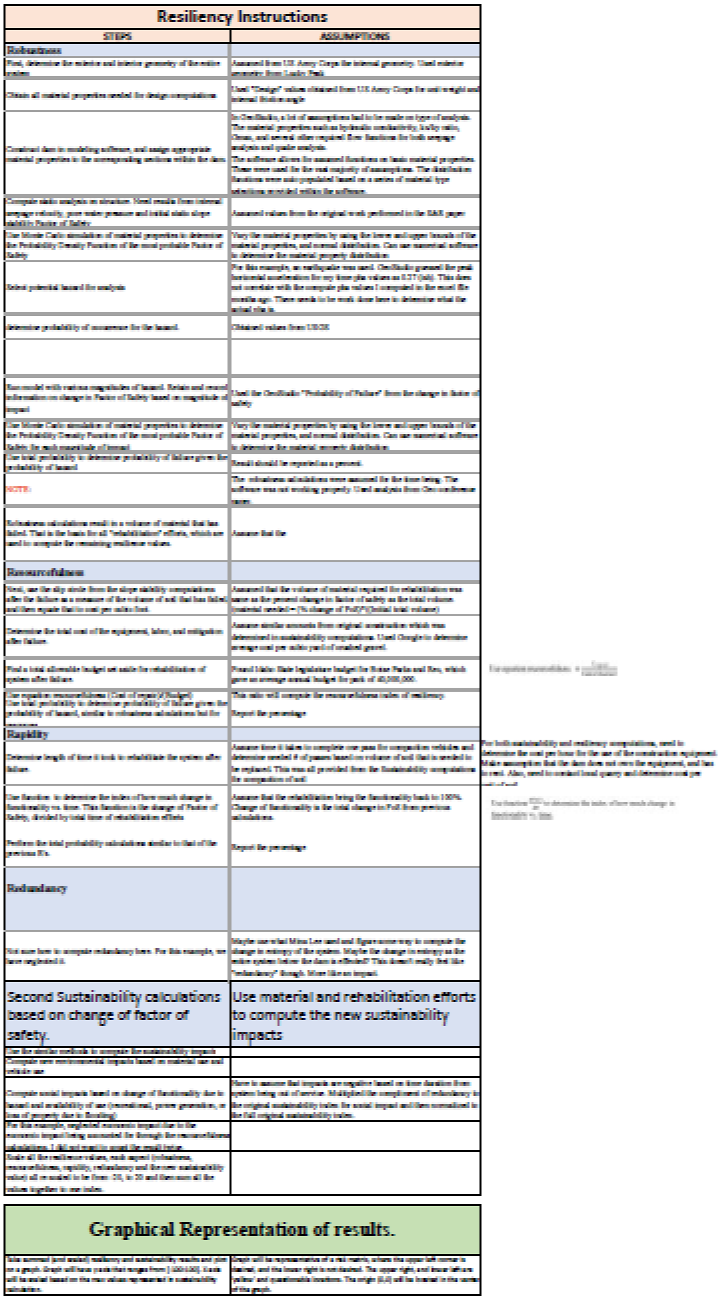
Excel File Pages

This appendix section provides an example sheet of the computations and inputs used to compute both sustainability and resiliency. The format for the spreadsheet included an introduction page that outlined the formulas and methods to compute both sustainability and resiliency. Next, the user defined input values were segregated out from the rest of the computations. This allows for the user to input known values such as known density or unit weight of the soil, travel distance to a quarry, type of hazard for the analysis and probabilities of the known hazard. Next, the calculations for sustainability used the user defined input to compute the social, economic and environmental computations. The values were all normalized to the overall cost of the structure and set to a unit of dollars per year ($/yr.). Resiliency computations were similarly computed by linking the user input values to determine the values for the four “R” pillars of resiliency, as well as the additional sustainability computations given the occurrence of a catastrophic event. Bayesian analysis was performed during this step to compute a most probable outcome given the input data. Finally, the results are shown in a separate sheet that clearly separates the four “R’s” of resiliency as well as compiles all the intermediate values for sustainability. A graph is represented on the final sheet to depict exactly where the resiliency rating falls for ease of understanding.



Sustainability Instructions

STEPS | ASSUMPTIONS



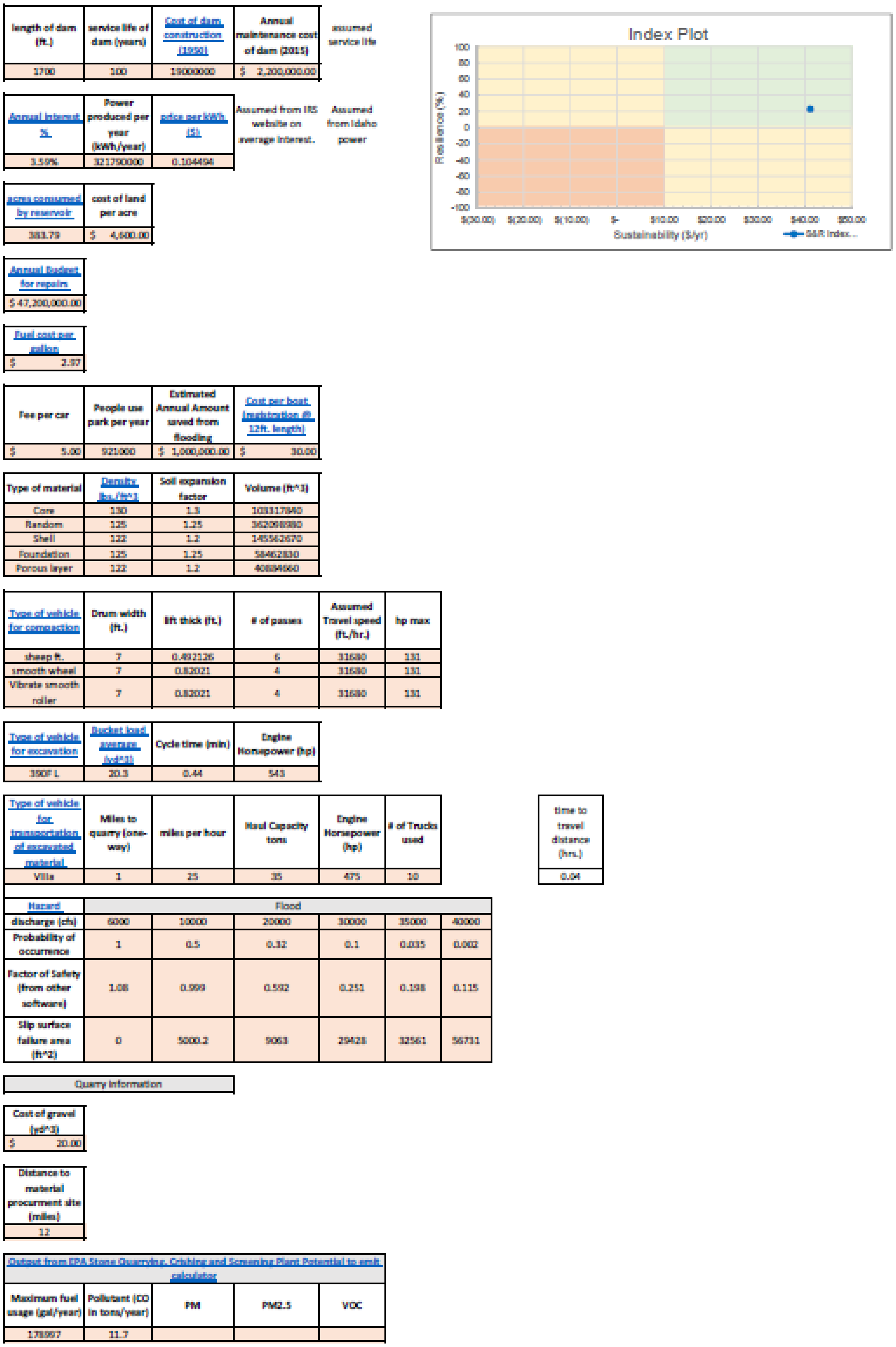
Resiliency Instructions

STEPS | ASSUMPTIONS

Second Sustainability calculations based on change of factor of safety.

Use material and rehabilitation efforts to compute the new sustainability impacts

Graphical Representation of results.



length of dam (ft.)	service life of dam (years)	Cost of dam construction (1950)	Annual maintenance cost of dam (2015)
1700	100	19000000	$ 2,200,000.00

assumed service life

Annual interest %	Power produced per year (kWh/year)	price per kWh ($)
3.59%	321790000	0.104494

Assumed from IRS website on average interest.

Assumed from Idaho power

acres consumed by reservoir	cost of land per acre
383.79	$ 4,600.00

Annual Budget for repairs
$ 47,200,000.00

Fuel cost per gallon
$ 2.97

Fee per car	People use park per year	Estimated Annual Amount saved from flooding	Cost per boat (registration @ 12ft. length)
$ 5.00	921000	$ 1,000,000.00	$ 30.00

Type of material	Density (lbs./ft^3)	Soil expansion factor	Volume (ft^3)
Core	130	1.3	103317840
Random	125	1.25	362098980
Shell	122	1.2	145562670
Foundation	125	1.25	58462830
Porous layer	122	1.2	40884660

Type of vehicle for compaction	Drum width (ft.)	lift thick (ft.)	# of passes	Assumed Travel speed (ft./hr.)	hp max
sheep ft.	7	0.492126	6	31680	131
smooth wheel	7	0.82021	4	31680	131
Vibrate smooth roller	7	0.82021	4	31680	131

Type of vehicle for excavation	Bucket load average (yd^3)	Cycle time (min)	Engine Horsepower (hp)
390F L	20.3	0.44	543

Type of vehicle for transportation of excavated material	Miles to quarry (one-way)	miles per hour	Haul Capacity tons	Engine Horsepower (hp)	# of Trucks used
Villa	1	25	35	475	10

time to travel distance (hrs.)
0.04

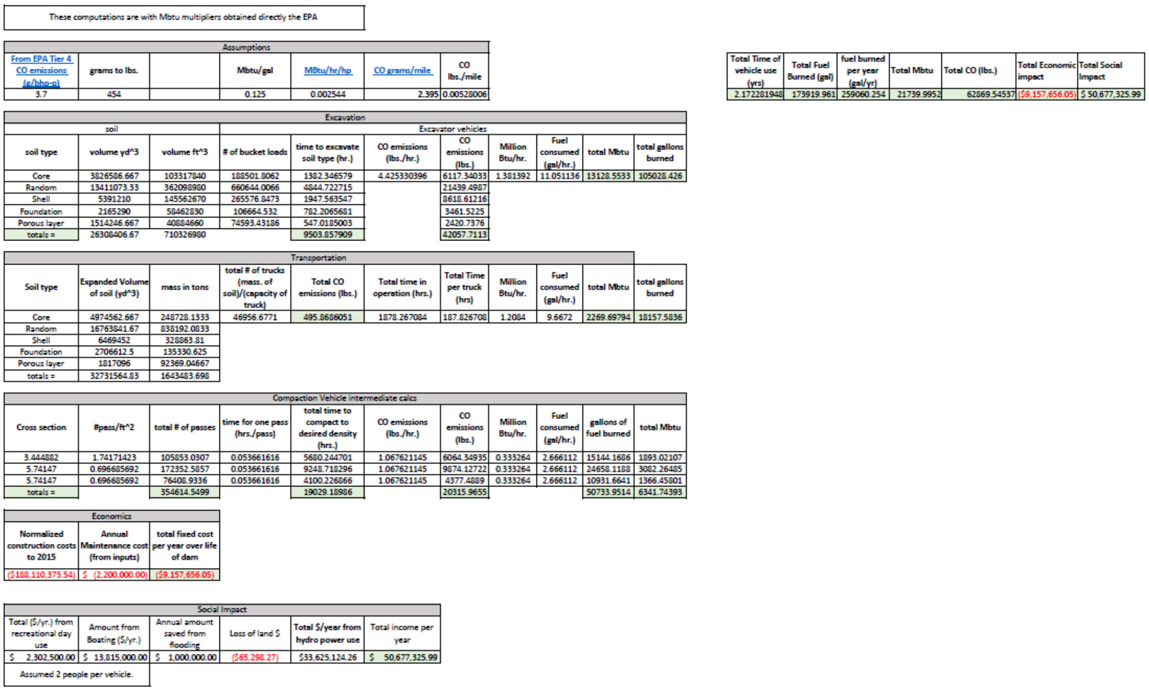
Hazard	Flood					
discharge (cfs)	6000	10000	20000	30000	35000	40000
Probability of occurrence	1	0.5	0.32	0.1	0.035	0.002
Factor of Safety (from other software)	1.08	0.999	0.592	0.251	0.198	0.115
Slip surface failure area (ft^2)	0	5000.2	9063	29428	32561	56731

Quarry information

Cost of gravel (yd^3)
$ 20.00

Distance to material procurment site (miles)
12

Output from EPA Stone Quarrying, Crshing and Screening Plant Potential to emit calculator				
Maximum fuel usage (gal/year)	Pollutant (CO in tons/year)	PM	PM2.5	VOC
178997	11.7			



These computations are with Mbtu multipliers obtained directly the EPA

Assumptions						
From EPA Tier 4 CO emissions (g/bhp-p)	grams to lbs.		Mbtu/gal	MBtu/hr/hp	CO grams/mile	CO lbs./mile
3.7	454		0.125	0.002544	2.395	0.00528006

Total Time of vehicle use (yrs)	Total Fuel Burned (gal)	fuel burned per year (gal/yr)	Total Mbtu	Total CO (lbs.)	Total Economic impact	Total Social Impact
2.172281948	173919.961	259060.254	21739.9952	62869.54537	($9,157,656.05)	$ 50,677,325.99

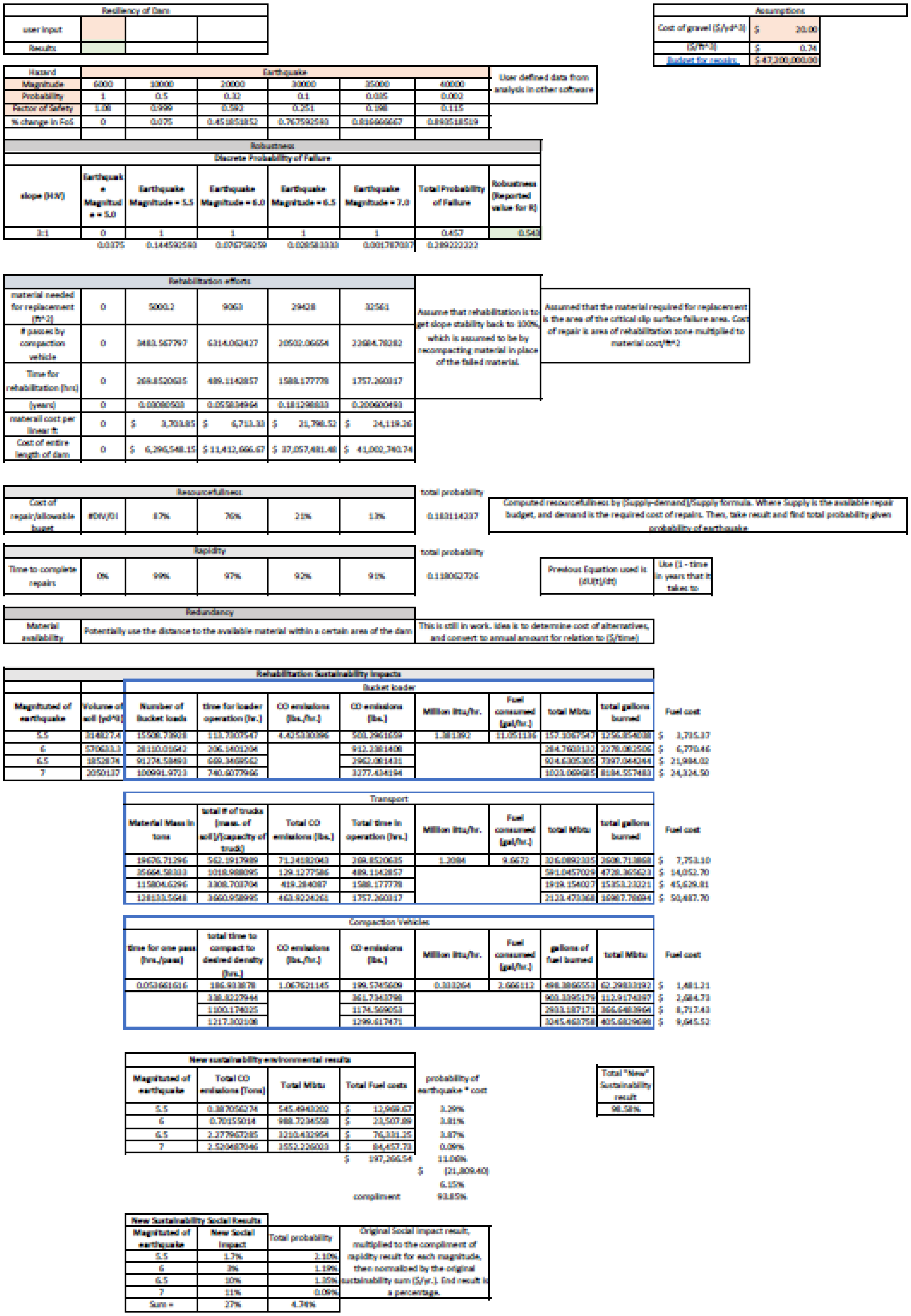
Excavation											
soil			Excavator vehicles								
soil type	volume yd^3	volume ft^3	# of bucket loads	time to excavate soil type (hr.)	CO emissions (lbs./hr.)	CO emissions (lbs.)	Million Btu/hr.	Fuel consumed (gal/hr.)	total Mbtu	total gallons burned
Core	3826586.667	103317840	188501.8062	1382.346579	4.425330396	6117.34033	1.381392	11.051136	13128.5533	105028.426
Random	13411073.33	362098980	660644.0066	4844.722715		21439.4987				
Shell	5391210	145562670	265576.8473	1947.563547		8618.61216				
Foundation	2165290	58462830	106664.532	782.2065681		3461.5225				
Porous layer	1514246.667	40884660	74593.43186	547.0185003		2420.7376				
totals =	26308406.67	710326980		9503.857909		42057.7113				

Transportation										
Soil type	Expanded Volume of soil (yd^3)	mass in tons	total # of trucks (mass. of soil)/(capacity of truck)	Total CO emissions (lbs.)	Total time in operation (hrs.)	Total Time per truck (hrs)	Million Btu/hr.	Fuel consumed (gal/hr.)	total Mbtu	total gallons burned
Core	4974562.667	248728.1333	46956.6771	495.8686051	1878.267084	187.826708	1.2084	9.6672	2269.69794	18157.5836
Random	16763841.67	838192.0833								
Shell	6469452	328863.81								
Foundation	2706612.5	135330.625								
Porous layer	1817096	92369.04667								
totals =	32731564.83	1643483.698								

Compaction Vehicle intermediate calcs										
Cross section	#pass/ft^2	total # of passes	time for one pass (hrs./pass)	total time to compact to desired density (hrs.)	CO emissions (lbs./hr.)	CO emissions (lbs.)	Million Btu/hr.	Fuel consumed (gal/hr.)	gallons of fuel burned	total Mbtu
3.444882	1.74171423	105853.0307	0.053661616	5680.244701	1.067621145	6064.34935	0.333264	2.666112	15144.1686	1893.02107
5.74147	0.696685692	172352.5857	0.053661616	9248.718296	1.067621145	9874.12722	0.333264	2.666112	24658.1188	3082.26485
5.74147	0.696685692	76408.9336	0.053661616	4100.226866	1.067621145	4377.4889	0.333264	2.666112	10931.6641	1366.45801
totals =		354614.5499		19029.18986		20315.9655			50733.9514	6341.74393

Economics		
Normalized construction costs to 2015	Annual Maintenance cost (from inputs)	total fixed cost per year over life of dam
($188,110,375.54)	$ (2,200,000.00)	($9,157,656.05)

Social Impact					
Total ($/yr.) from recreational day use	Amount from Boating ($/yr.)	Annual amount saved from flooding	Loss of land $	Total $/year from hydro power use	Total income per year
$ 2,302,500.00	$ 13,815,000.00	$ 1,000,000.00	($65,298.27)	$33,625,124.26	$ 50,677,325.99
Assumed 2 people per vehicle.					



Resiliency of Dam			
user input			
Results			

Assumptions	
Cost of gravel ($/yd^3)	$ 20.00
($/ft^3)	$ 0.74
Budget for repairs	$ 47,200,000.00

Hazard	Earthquake					
Magnitude	6000	10000	20000	30000	35000	40000
Probability	1	0.5	0.32	0.1	0.035	0.002
Factor of Safety	1.08	0.999	0.592	0.251	0.198	0.115
% change in FoS	0	0.075	0.451851852	0.767592593	0.816666667	0.893518519

User defined data from analysis in other software

Robustness							
Discrete Probability of Failure							
slope (H:V)	Earthquake Magnitude = 5.0	Earthquake Magnitude = 5.5	Earthquake Magnitude = 6.0	Earthquake Magnitude = 6.5	Earthquake Magnitude = 7.0	Total Probability of Failure	Robustness (Reported value for R)
3:1	0	1	1	1	1	0.457	0.543
	0.0375	0.144592593	0.076759259	0.028583333	0.001787037	0.289222222	

Rehabilitation efforts					
material needed for replacement (ft^2)	0	5000.2	9063	29428	32561
# passes by compaction vehicle	0	3483.567797	6314.062427	20502.06654	22684.78282
Time for rehabilitation (hrs)	0	269.8520635	489.1142857	1588.177778	1757.260317
(years)	0	0.03080503	0.055834966	0.181298833	0.200600493
materail cost per linear ft	0	$ 3,703.85	$ 6,713.33	$ 21,798.52	$ 24,119.26
Cost of entire length of dam	0	$ 6,296,548.15	$ 11,412,666.67	$ 37,057,481.48	$ 41,002,740.74

Assume that rehabilitation is to get slope stability back to 100%, which is assumed to be by recompacting material in place of the failed material.

Assumed that the material required for replacement is the area of the critical slip surface failure area. Cost of repair is area of rehabilitation zone multiplied to material cost/ft^2

Resourcefulness						total probability
Cost of repair/allowable buget	#DIV/0!	87%	76%	21%	13%	0.183114237

Computed resourcefulness by (Supply-demand)/Supply formula. Where Supply is the available repair budget, and demand is the required cost of repairs. Then, take result and find total probability given probability of earthquake

Rapidity						total probability
Time to complete repairs	0%	99%	97%	92%	91%	0.118062726

Previous Equation used is (dU(t)/dt)	Use (1 - time in years that it takes to

Redundancy		
Material availability	Potentially use the distance to the available material within a certain area of the dam	This is still in work. Idea is to determine cost of alternatives, and convert to annual amount for relation to ($/time)

Rehabilitation Sustainability Impacts

		Bucket loader								
Magnituted of earthquake	Volume of soil (yd^3)	Number of Bucket loads	time for loader operation (hr.)	CO emissions (lbs./hr.)	CO emissions (lbs.)	Million Btu/hr.	Fuel consumed (gal/hr.)	total Mbtu	total gallons burned	Fuel cost
5.5	314827.4	15508.73928	113.7307547	4.425330396	503.2961659	1.381392	11.051136	157.1067547	1256.854038	$ 3,735.37
6	570633.3	28110.01642	206.1401204		912.2381408			284.7603132	2278.082506	$ 6,770.46
6.5	1852874	91274.58493	669.3469562		2962.081431			924.6305305	7397.044244	$ 21,984.02
7	2050137	100991.9723	740.6077966		3277.434194			1023.069685	8184.557483	$ 24,324.50

Transport								
Material Mass in tons	total # of trucks (mass. of soil)/(capacity of truck)	Total CO emissions (lbs.)	Total time in operation (hrs.)	Million Btu/hr.	Fuel consumed (gal/hr.)	total Mbtu	total gallons burned	Fuel cost
19676.71296	562.1917989	71.24182043	269.8520635	1.2084	9.6672	326.0892335	2608.713868	$ 7,753.10
35664.58333	1018.988095	129.1277586	489.1142857			591.0457029	4728.365623	$ 14,052.70
115804.6296	3308.703704	419.284087	1588.177778			1919.154027	15353.23221	$ 45,629.81
128133.5648	3660.958995	463.9224261	1757.260317			2123.473368	16987.78694	$ 50,487.70

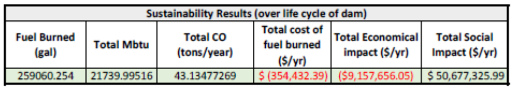
Compaction Vehicles								
time for one pass (hrs./pass)	total time to compact to desired density (hrs.)	CO emissions (lbs./hr.)	CO emissions (lbs.)	Million Btu/hr.	Fuel consumed (gal/hr.)	gallons of fuel burned	total Mbtu	Fuel cost
0.053661616	186.933878	1.067621145	199.5745609	0.333264	2.666112	498.3866553	62.29833192	$ 1,481.21
	338.8227944		361.7343798			903.3395179	112.9174397	$ 2,684.73
	1100.174025		1174.569053			2933.187171	366.6483964	$ 8,717.43
	1217.302108		1299.617471			3245.463758	405.6829698	$ 9,645.52

New sustainability environmental results				
Magnituted of earthquake	Total CO emissions (Tons)	Total Mbtu	Total Fuel costs	probability of earthquake * cost
5.5	0.387056274	545.4943202	$ 12,969.67	3.29%
6	0.70155014	988.7234558	$ 23,507.89	3.81%
6.5	2.277967285	3210.432954	$ 76,331.25	3.87%
7	2.520487046	3552.226033	$ 84,457.73	0.09%
			$ 197,266.54	11.06%
				$ (21,809.40)
				6.15%
			compliment	93.85%

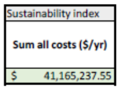
Total "New" Sustainability result
98.58%

New Sustainability Social Results		
Magnituted of earthquake	New Social Impact	Total probability
5.5	1.7%	2.10%
6	3%	1.19%
6.5	10%	1.35%
7	11%	0.09%
Sum =	27%	4.74%

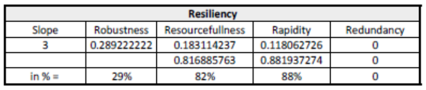
Original Social impact result, multiplied to the compliment of rapidity result for each magnitude, then normalized by the original sustainability sum ($/yr.). End result is a percentage.



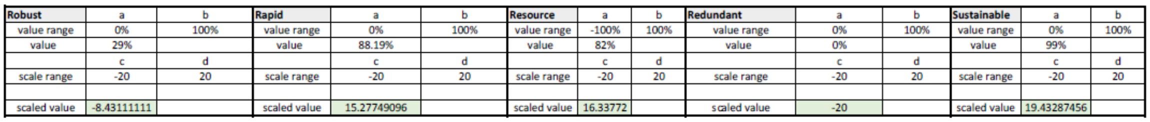
Sustainability Results (over life cycle of dam)					
Fuel Burned (gal)	Total Mbtu	Total CO (tons/year)	Total cost of fuel burned ($/yr)	Total Economical impact ($/yr)	Total Social Impact ($/yr)
259060.254	21739.99516	43.13477269	$ (354,432.39)	($9,157,656.05)	$ 50,677,325.99



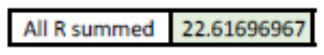
Sustainability index
Sum all costs ($/yr)
$ 41,165,237.55



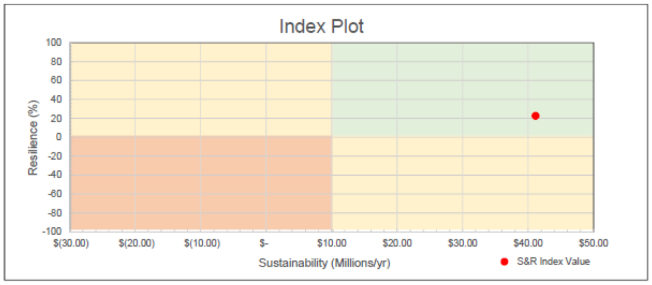
Resiliency				
Slope	Robustness	Resourcefullness	Rapidity	Redundancy
3	0.289222222	0.183114237	0.118062726	0
		0.816885763	0.881937274	0
in % =	29%	82%	88%	0



Robust	a	b	**Rapid**	a	b	**Resource**	a	b	**Redundant**	a	b	**Sustainable**	a	b
value range	0%	100%	value range	0%	100%	value range	-100%	100%	value range	0%	100%	value range	0%	100%
value	29%		value	88.19%		value	82%		value	0%		value	99%	
	c	d		c	d		c	d		c	d		c	d
scale range	-20	20	scale range	-20	20	scale range	-20	20	scale range	-20	20	scale range	-20	20
scaled value	-8.43111111		scaled value	15.27749096		scaled value	16.33772		scaled value	-20		scaled value	19.43287456	

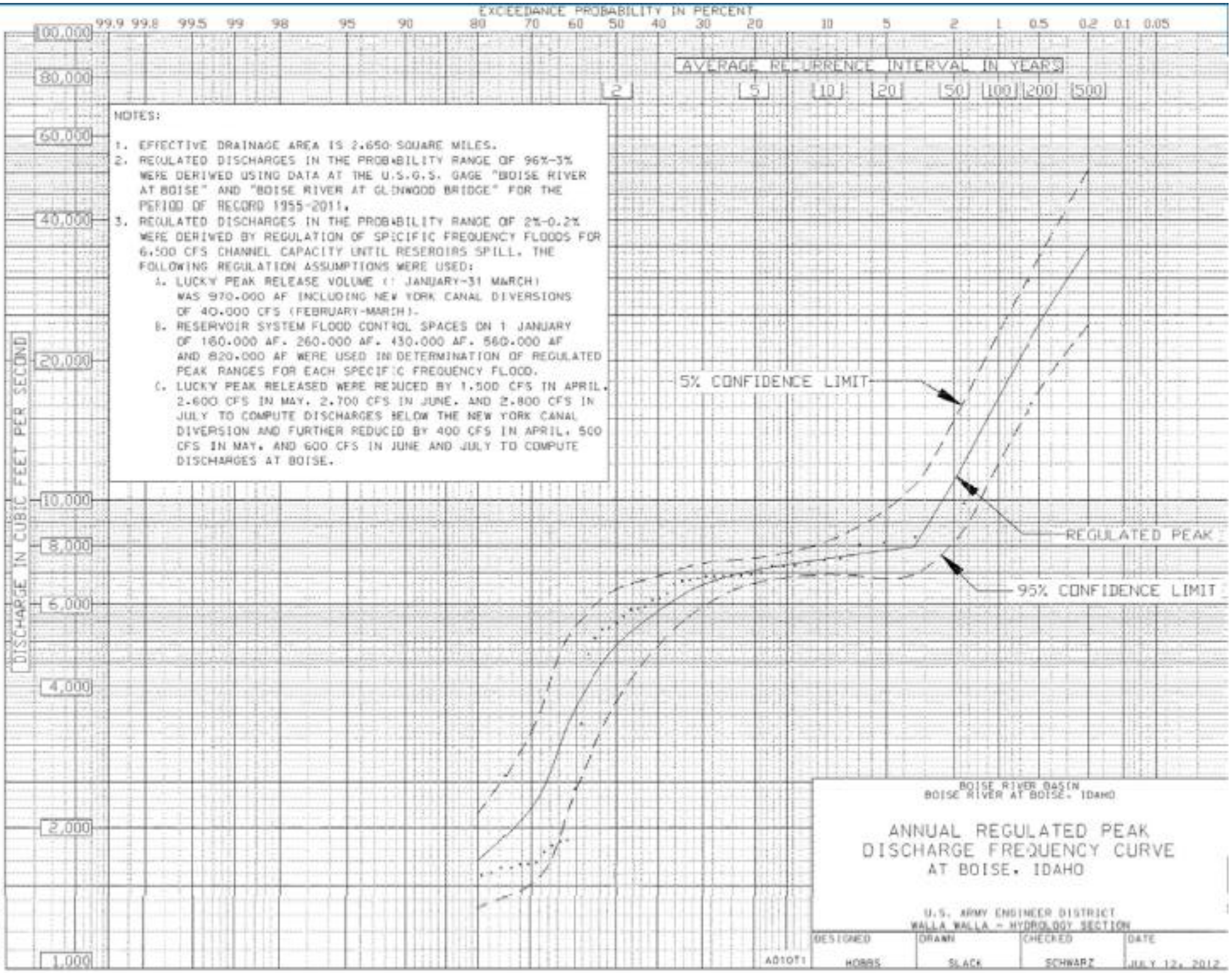


All R summed	22.61696967



Hydrograph

An exceedance probability chart was obtained from the USACE to assist in computing the probability of occurrence for flooding at Lucky Peak. From the chart, three lines are given with the associated confidence level. For the purpose of this research the assumption was made that the averaged line was most optimal for determining the exceedance peak flow.



NOTES:

1. EFFECTIVE DRAINAGE AREA IS 2,650 SQUARE MILES.
2. REGULATED DISCHARGES IN THE PROBABILITY RANGE OF 96%-3% WERE DERIVED USING DATA AT THE U.S.G.S. GAGE "BOISE RIVER AT BOISE" AND "BOISE RIVER AT GLENWOOD BRIDGE" FOR THE PERIOD OF RECORD 1955-2011.
3. REGULATED DISCHARGES IN THE PROBABILITY RANGE OF 2%-0.2% WERE DERIVED BY REGULATION OF SPECIFIC FREQUENCY FLOODS FOR 6,500 CFS CHANNEL CAPACITY UNTIL RESEROIRS SPILL. THE FOLLOWING REGULATION ASSUMPTIONS WERE USED:
   A. LUCKY PEAK RELEASE VOLUME (1 JANUARY-31 MARCH) WAS 970,000 AF INCLUDING NEW YORK CANAL DIVERSIONS OF 40,000 CFS (FEBRUARY-MARCH).
   B. RESERVOIR SYSTEM FLOOD CONTROL SPACES ON 1 JANUARY OF 160,000 AF, 260,000 AF, 430,000 AF, 560,000 AF AND 820,000 AF WERE USED IN DETERMINATION OF REGULATED PEAK RANGES FOR EACH SPECIFIC FREQUENCY FLOOD.
   C. LUCKY PEAK RELEASED WERE REDUCED BY 1,500 CFS IN APRIL, 2,600 CFS IN MAY, 2,700 CFS IN JUNE, AND 2,800 CFS IN JULY TO COMPUTE DISCHARGES BELOW THE NEW YORK CANAL DIVERSION AND FURTHER REDUCED BY 400 CFS IN APRIL, 500 CFS IN MAY, AND 600 CFS IN JUNE AND JULY TO COMPUTE DISCHARGES AT BOISE.

BOISE RIVER BASIN
BOISE RIVER AT BOISE, IDAHO

ANNUAL REGULATED PEAK
DISCHARGE FREQUENCY CURVE
AT BOISE, IDAHO

U.S. ARMY ENGINEER DISTRICT
WALLA WALLA - HYDROLOGY SECTION

DESIGNED	DRAWN	CHECKED	DATE
HOBBS	SLACK	SCHWARZ	JULY 12, 2012

A01OF1

PLATE 2