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# Unified Risk-Based Assessment Framework to Assess Sustainability and Resiliency of Civil Infrastructure

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# Unified Risk-Based Framework to Assess Sustainability and Resiliency of Civil Infrastructure

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**Abstract**; Sustainable development, which identifies civil infrastructure impact on the environment, economy, and society has become a major focus in research. Civil infrastructure inherently has a direct connection with all three aspects of sustainability. As major climate events pose a threat to infrastructure, the potentiality of failure may increase with non-robust designs. In consideration of risk, as well as the need for sustainable development, a unified assessment method is required to measure the quality of civil infrastructure. Proposed here is a unified assessment method that balances the resiliency and sustainability of civil infrastructure by the risk of occurrence of catastrophic events.

## Methods;

- Performed literature review
- Develop a quantitative and unified assessment framework.
- Perform analysis on chosen an example system of civil infrastructure.
- Quantify individual sustainability and resiliency.
- Display graphically index on risk matrix.

Sustainability – the ability for society to meet their needs without hindering future generations ability to meet their own. Balance between the economics, social, and environmental resources.

Measures of sustainability:

- Embodied energy
- Emissions
- Costs/revenue
- Prevention of property damage

Resiliency – The ability of a system to withstand an unusual perturbation and to recover efficiently from the damage induced by such perturbation.

Measures of resiliency:

- Change in functionality
- Available budget for repairs
- Location, and procurement of repair material
- Additional systems that can be used in the event of failure

## Sustainability Calculations

**Sustainability Calculations**: · Performed static analysis on earthen dam · Measured volume of material based on geometry of dam · Computed environmental, social, and economic impacts

All sustainability impacts related as annual worth over the design life of the dam, and summed together as one index value.

**Environmental Impacts:** Used brake-horse power and reported horsepower from vehicle specifications provided by manufacturers to determine total potential to emit. Based on EPA emission standards which use horsepower (g/(bhp-hr.)).

Conversion method for total emissions:

$$\frac{3.7\ grams}{bhp-hr},\ \frac{0.125\ Mbtu}{gal},\ \frac{0.002544\ MBtu/hr}{hp}$$

MMBtu (137,000 Btu/gal)

$$\left[\frac{lbs}{hr.}\right] = \left[\frac{grams}{bhp.-hr}\right] \cdot bhp_{max} \cdot \frac{1\ lb.}{454\ grams}.$$

| Environmental impact results | | |
|---|---|---|
| Fuel Burned (gal) | Total MBtu | Total CO (lbs.) |
| 174,000.00 | 22,000.00 | 63,000.00 |

**Economic Impacts:** Impacts based on historical data. Construction costs = $19 million in 1949. Average maintenance costs = $2.2 million in 2015. Average annual inflation rate 3.5%. Design life of dam is 100 years. Calculations used for conversion to future value,

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

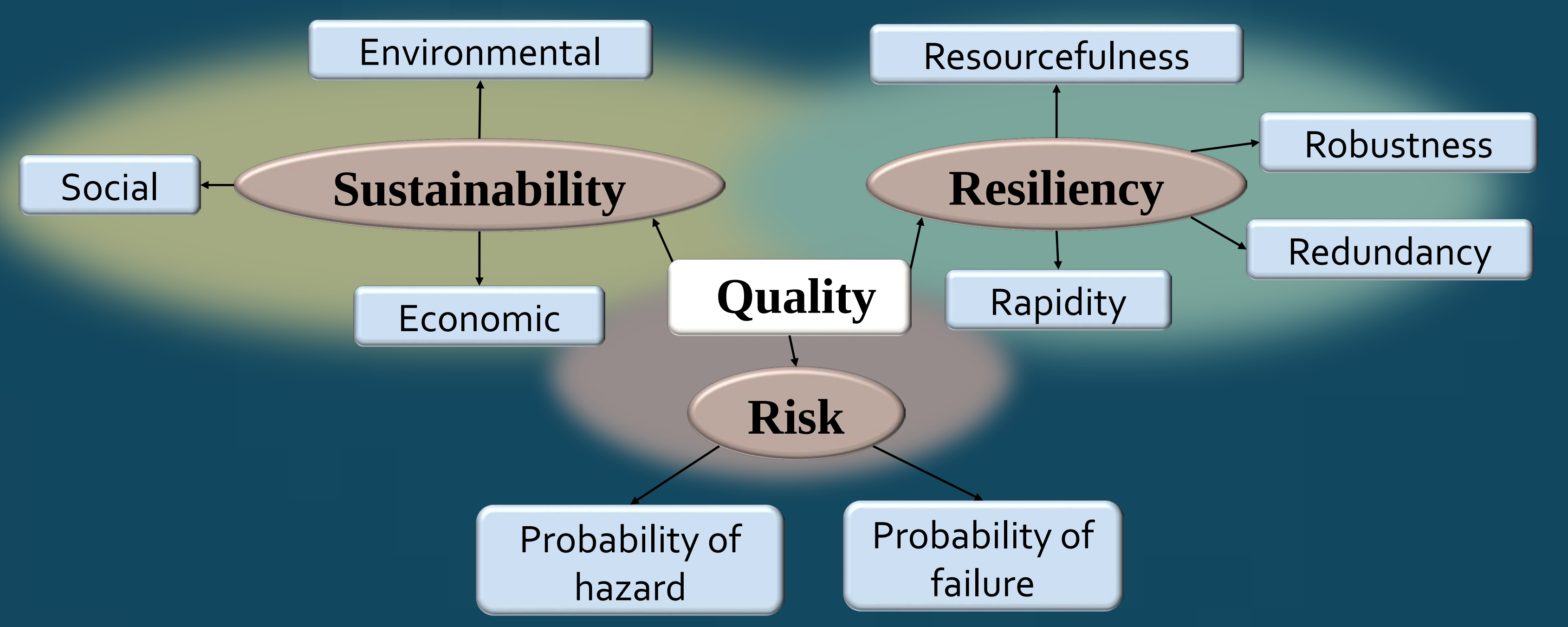
**Social Impacts:** Impacts included recreational uses, hydropower production, loss of land use due to reservoir. Cost to users 0.104 $\$/kWh$. Annual hydropower generated 322,000,000 $kWh/year$ (US Army Corps of Engineers. (2017)). Estimated usage via USACE ~ 921,000 people. Fee per car (day use) $5.00. Registration cost per 12 ft. boat $30.00. Average cost per acre of land $4,600.00. Estimate annual amount saved from flood damage ~ $1,000,000.00

| Sustainability Results | | |
|---|---|---|
| Environmental impact ($/yr.) | Economic impact ($/yr.) | Social Impact ($/yr.) |
| $ 240,000.00 | ($9,200,000.00) | $ 51,000,000.00 |

**Model**; Obtained material properties for Lucky Peak earthen dam from the U.S. Army Corps of Engineers. Probabilistic analysis was used to vary the material properties. Modeled earthquakes to simulate most probable seismic activity at Lucky Peak.

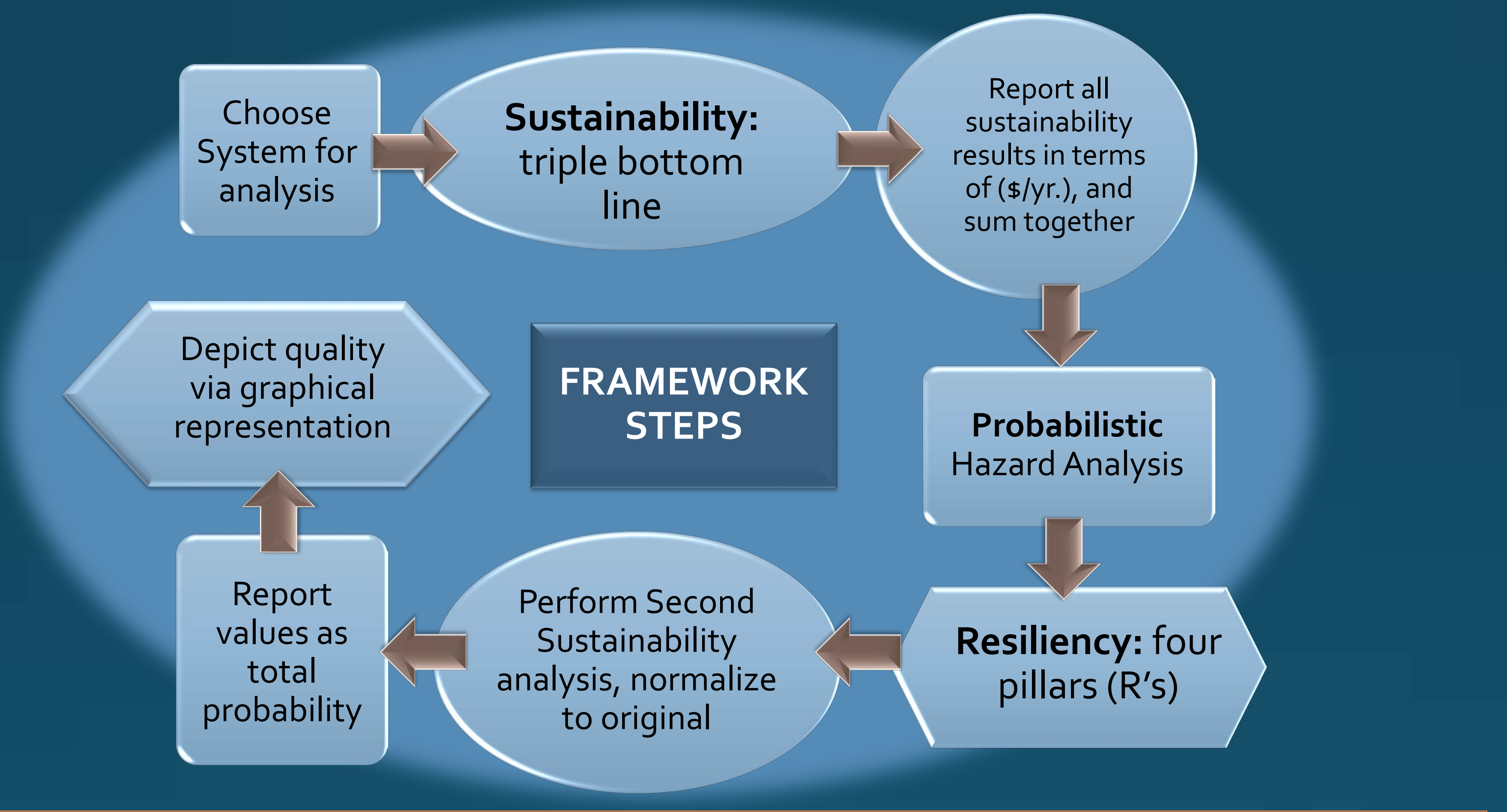
**Model Analysis:** Consisted of several steps · Steady-State Seepage · Slope Stability · Seismic Analysis · Transient Seepage Analysis · Second Slope Stability

| | 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) (γ') $(lb/ft^3)$ | 130 | 124 | 125 | 127 | 125 | 130 |
| Unit Weight (Sat.) (γ') $(lb/ft^3)$ | 135 | 130 | 135 | 135 | 140 | 135 |



## Framework

- ➢ Resiliency assessments are to be determined by probabilistic hazard analysis.
  - ✓ Results from the resiliency assessment will be reported as a total probability.
- ➢ Sustainability assessments will be performed twice, once as a static analysis for the initial construction of the infrastructure, and again after the impact of a low probable high consequence event.
  - ✓ Sustainability assessments will be reported as an annual worth over the design life of the dam.
- ➢ Index values for both sustainability and resiliency will then be plotted on a risk matrix type graph, depicting the overall quality of the system.


FRAMEWORK STEPS

Choose System for analysis

**Sustainability:** triple bottom line

Report all sustainability results in terms of ($/yr.), and sum together

Probabilistic Hazard Analysis

**Resiliency:** four pillars (R's)

Perform Second Sustainability analysis, normalize to original

Report values as total probability

Depict quality via graphical representation

**Hazard Analysis**: Potential hazards were determined based on location of the dam. Earthquakes were analyzed as a mode to cause failure. Probability of occurrence of Peak Horizontal Acceleration (PHA) for various earthquakes were obtained from the U.S. Geological Survey. Relations between PHA and magnitude of earthquake was made by use of the Modified Mercalli Intensity scale to associate Peak Horizontal Acceleration (USGS (2017); Robbins et al. (2018)). Performed probabilistic hazard analysis to identify the potentiality of failure.

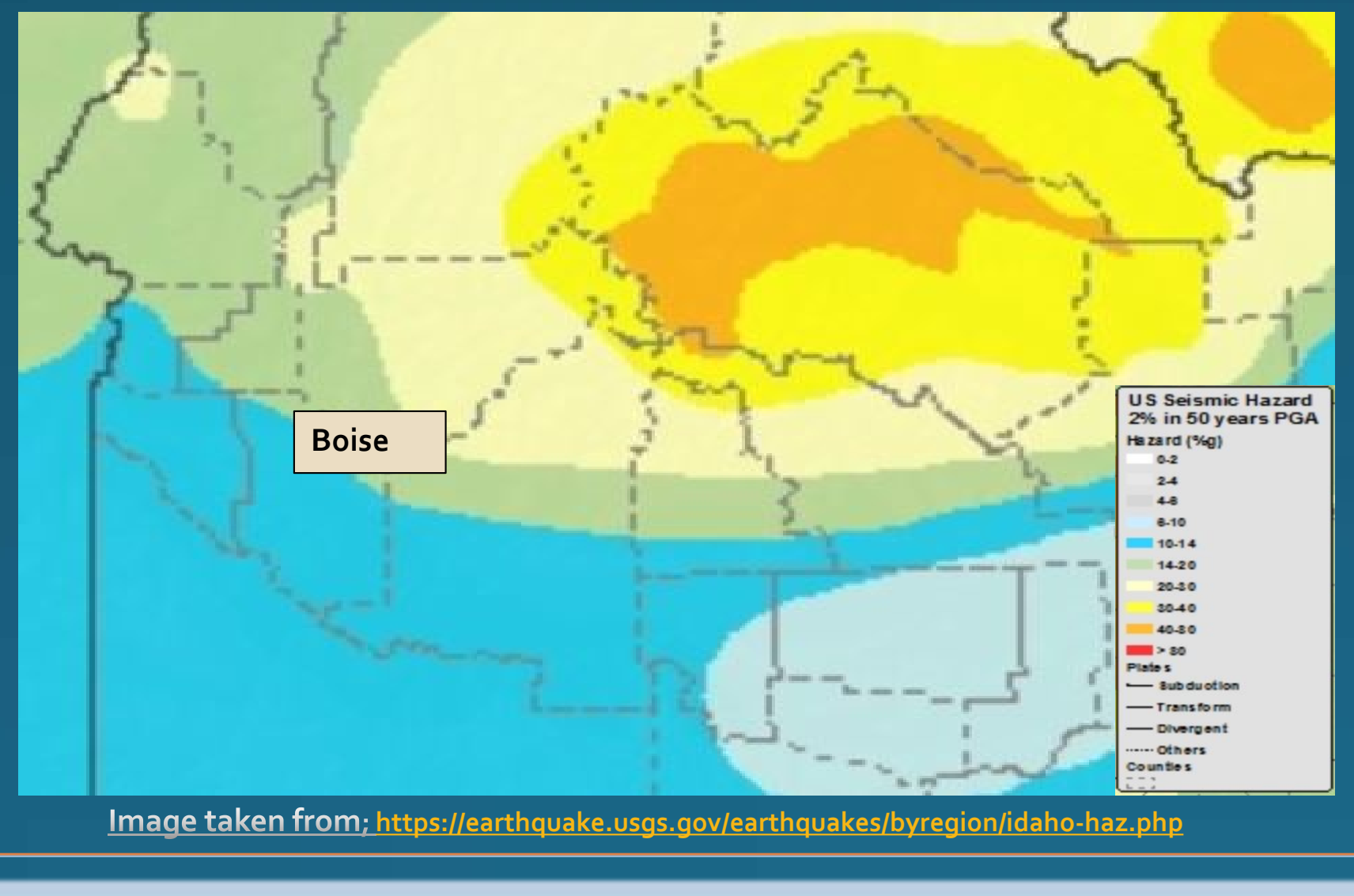


Image taken from; https://earthquake.usgs.gov/earthquakes/byregion/idaho-haz.php

**References**; Basu, D., Misra, A., and Puppala, A. J. (2015). "Sustainability and geotechnical engineering: perspectives and review." Canadian Geotechnical Journal, 52(1), 96–113.
Bocchini, P., ASCE, M., Frangopol, D. M., ASCE, D. M., Ummenhofer, T., and Zinke, T. (2014). "Resilience and Sustainability of Civil Infrastructure : Toward a Unified Approach." Journal of Infrastructure Systems, 20(2), 1–16.
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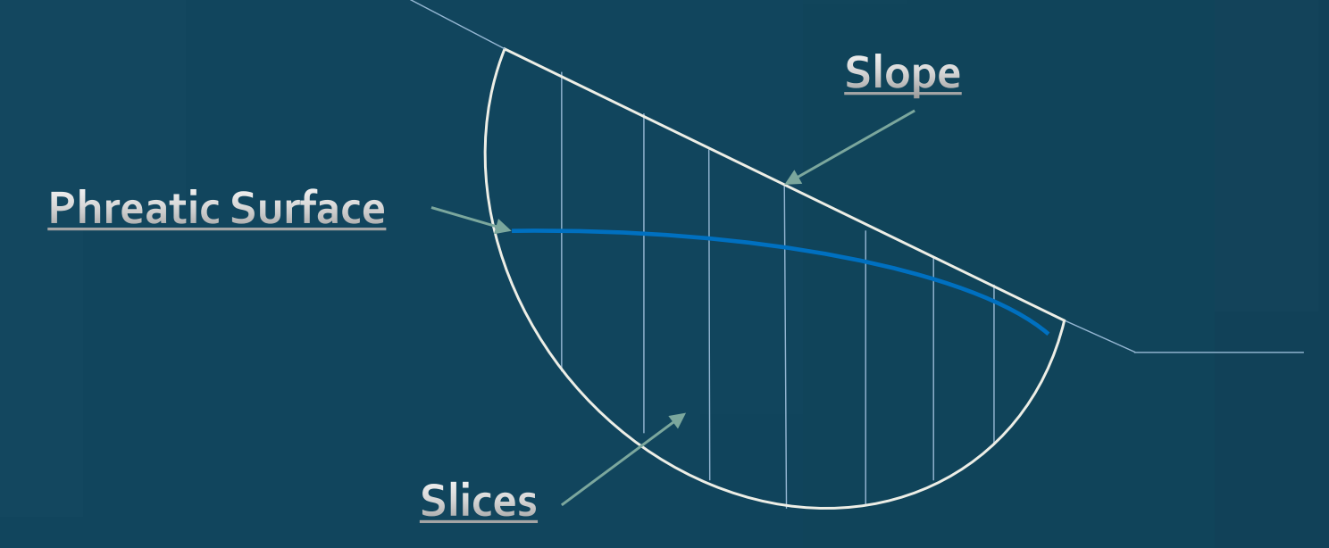
## Resiliency Calculations

**Resiliency Calculations**: · Measured robustness by determining change in factor of safety · Use required material volumes as bases for measuring rehabilitation efforts · Computed additional sustainability impact assessment · Related all resiliency metrics as total probability

**Robustness:** Change in Factor of Safety was measured by using the Bishop's Method of Slices. The method of slices includes drawing a circle on the slope of the dam, dividing the circle into rectangular sections. Each rectangular section is considered as a "slice" of the circle. The geometry of each slice and the material properties within the respective slice is used to compare the shear resistance of the slope to the shear created by the mass of the soil. The resulting Factor of Safety was accompanied with a probability of failure given the occurrence of an earthquake. A probability of occurrence for each magnitude and the total probability of failure was computed by use of the formula; $Robustness = P(A \cap B)$. Where A is the probability of an earthquake occurring, and B is the probability of failure given that a certain magnitude of earthquake occurred.



$$\text{Factor of Safety} = \frac{\tau_f}{\tau_m}$$

Where: $\tau_f$ is the available shear strength of the soil, and $\tau_m$ is the minimum shear strength required to maintain stability.

| Robustness | | | | | | |
|---|---|---|---|---|---|---|
| Discrete Probability of Failure | | | | | | |
| slope (H:V) | Earthquake Mag = 5.5 | Earthquake Mag = 6.0 | Earthquake Mag = 6.5 | Earthquake Mag = 7.0 | Total Probability of Failure | Robustness (Reported value) |
| 3:1 | 0 | 0.0465 | 0.994 | 0.986 | 0.054 | 0.946 |

**Resourcefulness**: Volume of material required to complete repairs was used to compute cost, time and effort for repairs. The repair costs for each magnitude of earthquake were determined, and compared to the available maintenance budget provided by legislation to the Walla Walla district Army Corps of Engineers. A total probability for the resourcefulness was computed similarly to that of the robustness.

$$Resourcefulness = \frac{Budget\ - Cost}{Budget}$$

| Resourcefulness | | | | | | |
|---|---|---|---|---|---|---|
| | Mag. 5.5 | Mag. 6.0 | Mag. 6.5 | Mag. 7.0 | Total Probability | Reported value |
| Cost of repair/allowable budget | 67% | 34% | 1% | -31% | 0.306 | 0.694 |

**Rapidity**: The rapidity was determined as the time to repair the dam using the available material and equipment. The repair duration was then normalized to the original time it took to construct the dam. Results reported as the total probability for rapidity.

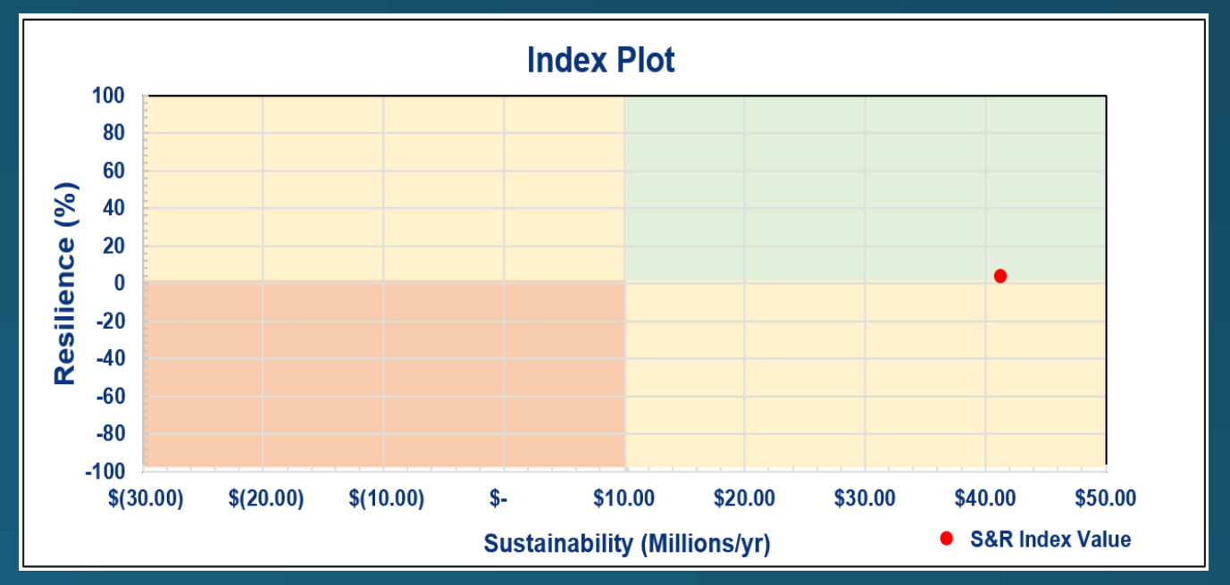
| Rapidity | | | | | | |
|---|---|---|---|---|---|---|
| Mag. | 5.5 | 6 | 6.5 | 7 | Total Probability | Reported Value |
| Rapidity of system | 97% | 93% | 90% | 86% | 0.112 | 0.888 |

**Second Sustainability Calculations**: A second computation of the sustainability impacts after the occurrence of an earthquake was computed. The results were normalized to the original sustainability values, and then reported as a total probability given the occurrence of an earthquake.

| Total "New" Sustainability result |
|---|
| 87.43% |

**Results**; Results from all resiliency indexes were summed scaled to range from (-20,20), then summed together. Sustainability results were also summed together, and the results were plotted on a risk-type graph.

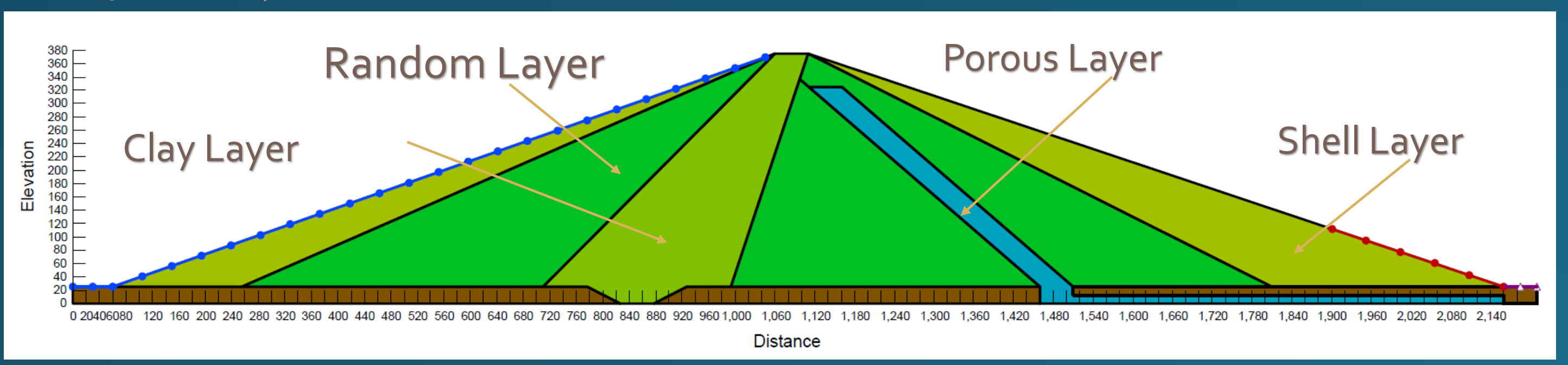
| Sustainability index | Resiliency Index |
|---|---|
| Sum all costs ($/yr.) | **Sum all 'R' indices** |
| $41,000,000.00 | 3.43 |



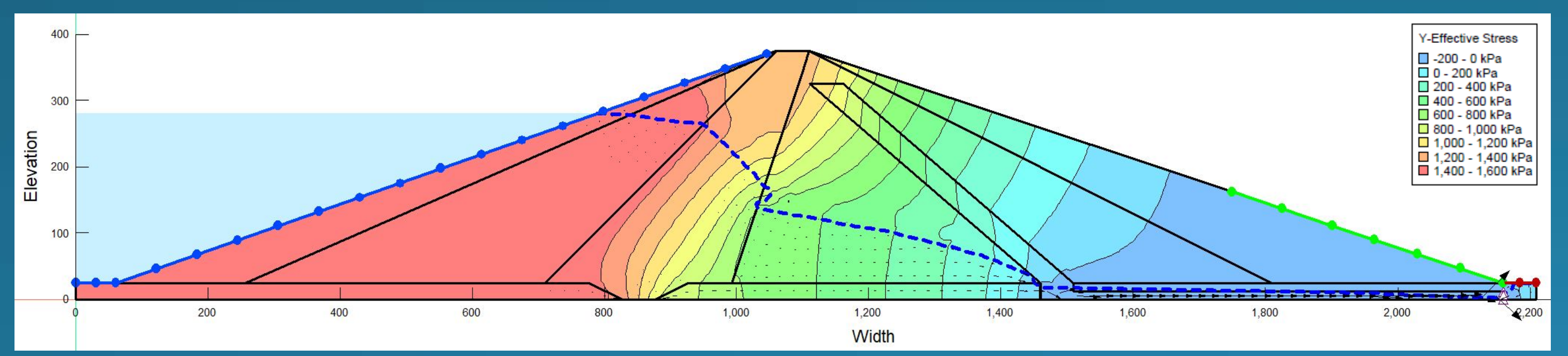
## Future Work:

- Framework validation is required as a next step.
- Two more systems will be analyzed to validate the predictability of the assessment framework.
- Monte Carlo simulations will be performed on variability of sustainability input values.
- All index values will be reported as single index value.

**Model;** Material Layout



**Model :** Dynamic Quake Analysis



**Model :** Slope Stability (Bishop's Method of Slices)