Arizona State University
Transportation Systems Planning Class
Tools for Managing Transportation System Resilience

Steven Olmsted – Arizona Department of Transportation – November 2022

Agency Snapshot

ADOT Annual Construction Program

$1,300,000,000

Arizona Long Term Transportation Revenue Projections

$25,000,000,000

Arizona Long Term Transportation System Need

$100,000,0000,000

Agency Snapshot

Arizona

- 140,000 maintenance lane miles
- 8,000 bridges
- 1 International border

ADOT

- 30,000 maintenance lane miles connecting those 140,000
- 5,000 bridges
- 7 maintenance/construction districts
- 1,500 facility buildings

Spread over 114,000 square miles

Operating from sea level to 8,000 feet

Temperatures below 0°F to over 120°F

Agency Resilience

Critical Transportation Infrastructure Protection

State

- Arizona State Emergency Response and Recovery Plan (SERRP)
- Planning Branch – AZ Department of Emergency and Military Affairs

ADOT

- Emergency Preparedness Management
- Business Continuity - pandemic - Director's Office revamp
- Roadway - Incident Response Unit
- Physical, chemical, biological – dedicated Emergency Manager
- Road Weather AZ 511 app / ADOT Alerts app
- Cyber - IT Security Risk Management & Compliance team
- Transportation Infrastructure - Weather & Natural Hazard

Transportation Infrastructure Resilience

FHWA 5520 - anticipate, prepare for, and adapt to changing conditions and withstand, respond to, and recover rapidly from disruptions

Program Definition - The management of assets (bridges, culverts, pavement, and roadside vegetation/stabilization) in relation to the extreme weather-climate risks of; intense precipitation, system flooding, wildfires, wildfire-induced floods, drought-related dust storms, rockfall incidents, slope failures, and measurable climate trends (especially as it relates to precipitation and direct effects of increased surface temperatures); by regions or specific segments, emphasized as critical to contribute to the safety of the traveling public, improve weather and natural hazard risk management, and improve the long term life cycle planning of transportation infrastructure.

Eligible Risk Inventory

- Agency - political, financial, reputational
- Environmental - natural hazard, extreme weather, future climate
- Infrastructure - road and bridge failure
  - Intense Precipitation
  - System Flooding
  - Wildfires
  - Wildfire-Induced Floods
  - Drought-Related Dust Storms
  - Rockfall Incidents
  - Slope Failures and Subsidence
  - Increased Surface Temperatures

Eligible Risk Inventory

Eligible Risk Inventory

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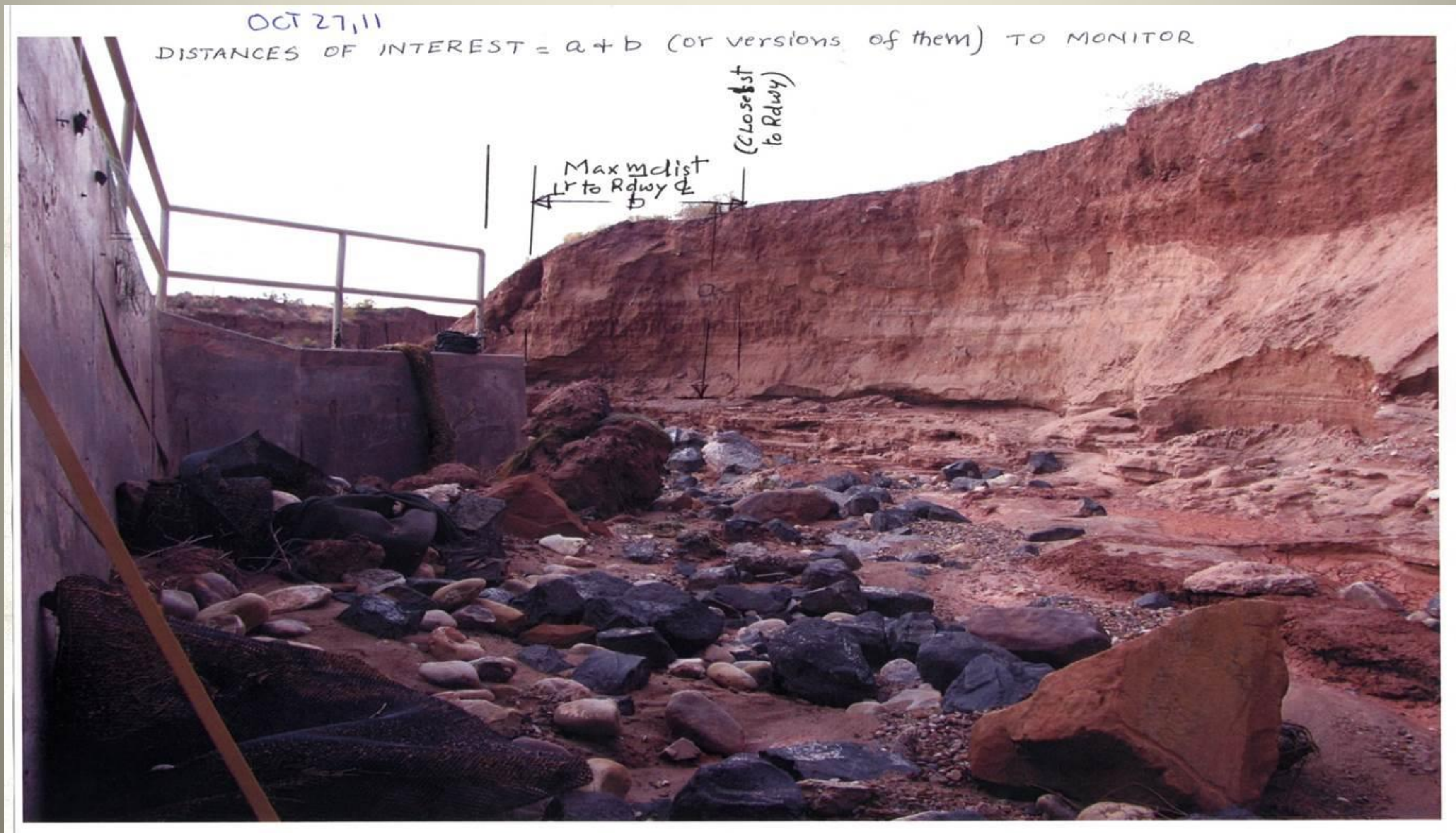
Eligible Risk Inventory



Eligible Risk Inventory

Eligible Risk Inventory

Eligible Risk Inventory

September 2022

September 2022

September 2022

September 2022

Resilience Building Example #1

State Route 191 - Mile Post 436 to Chinle – Chinle, AZ – Navajo Nation

Resilience Building Example #1

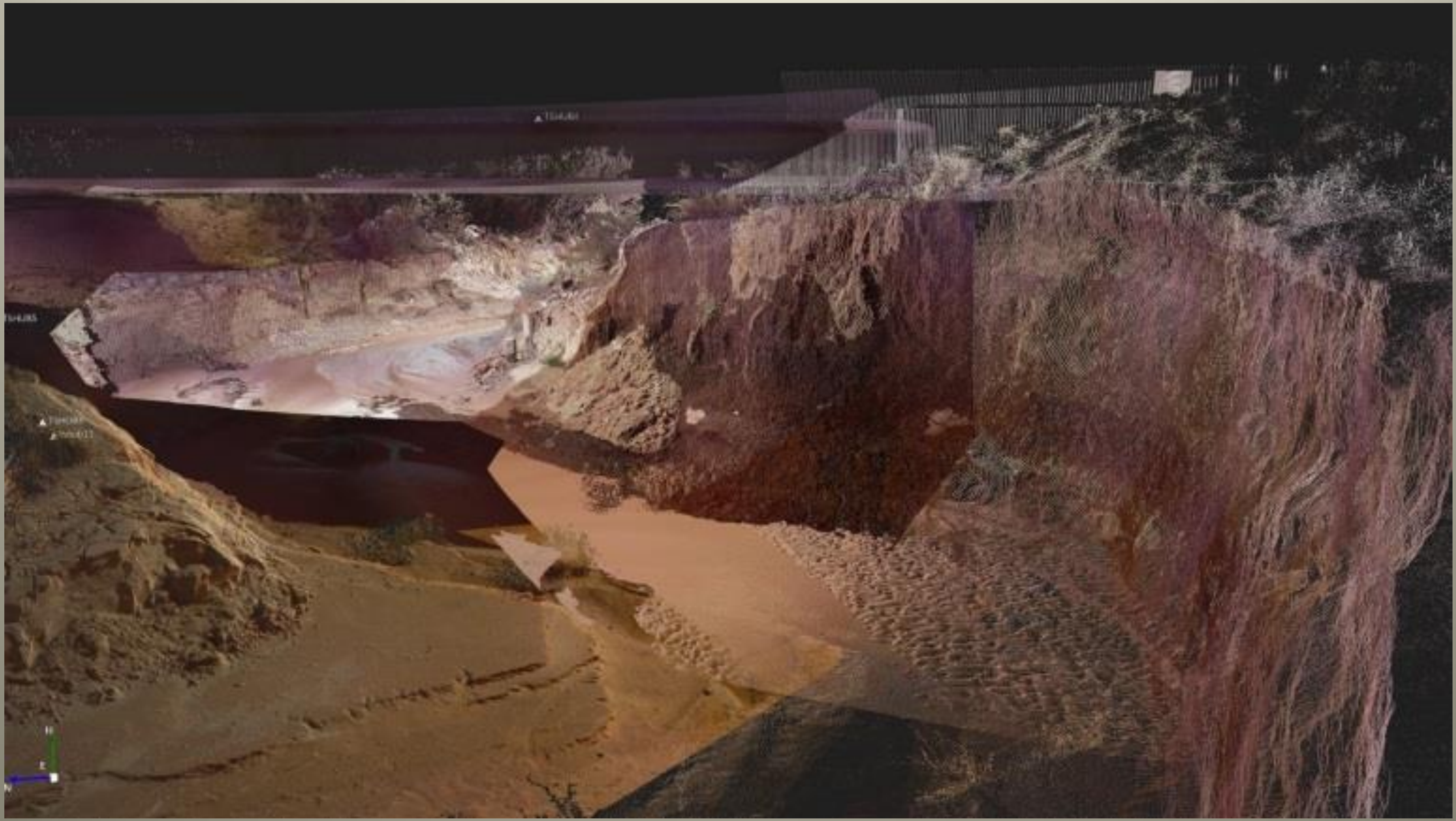
- Protect the new $5.2M roadway investment
- Address severe erosional and drainage issues that has led to a 25%-100% degradation at sixty-one (61) of the eighty-six (86) CMP drainage structures
- Address drainage capacity and slope stabilization issues at those structures and severely compromised stormwater management capabilities along this segment of SR 191
- Upgrade ADOT’s application of risk-based assessment modeling at the asset class, project development, and localized hydrology
- Further ensure use of SR 191 in the remote far northwest of Arizona and a main Apache County connector between SR 264 and US 160 in the advent of an extreme weather event
- Improve transportation system access - Hopi Tribe and Navajo Nation

Resilience Building Example #1

State Route 191 - Mile Post 436 to Chinle – Chinle, AZ – Navajo Nation

Resilience Building Example #2

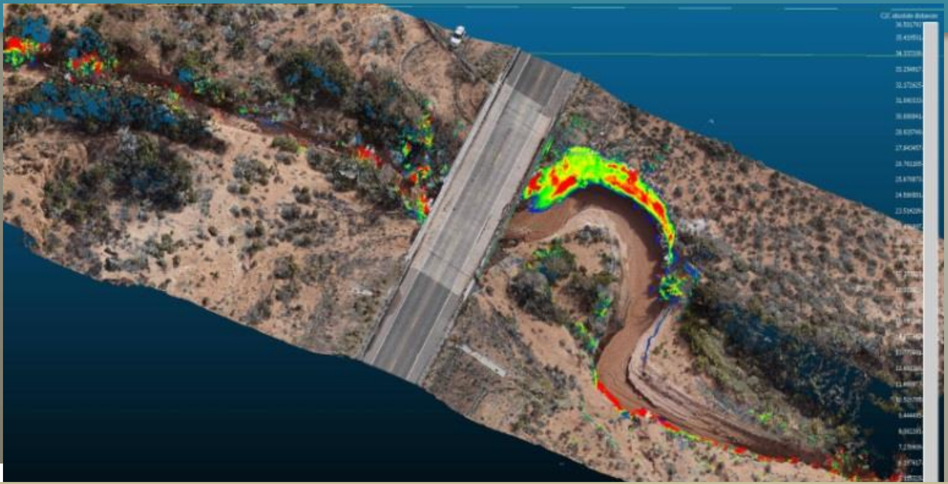
State Route 160 - Laguna Creek Bridge – Dennehotso, AZ



USGS Partnership - Reach Monitoring in Dynamic Channels
Understanding bank erosion and impacts to infrastructure

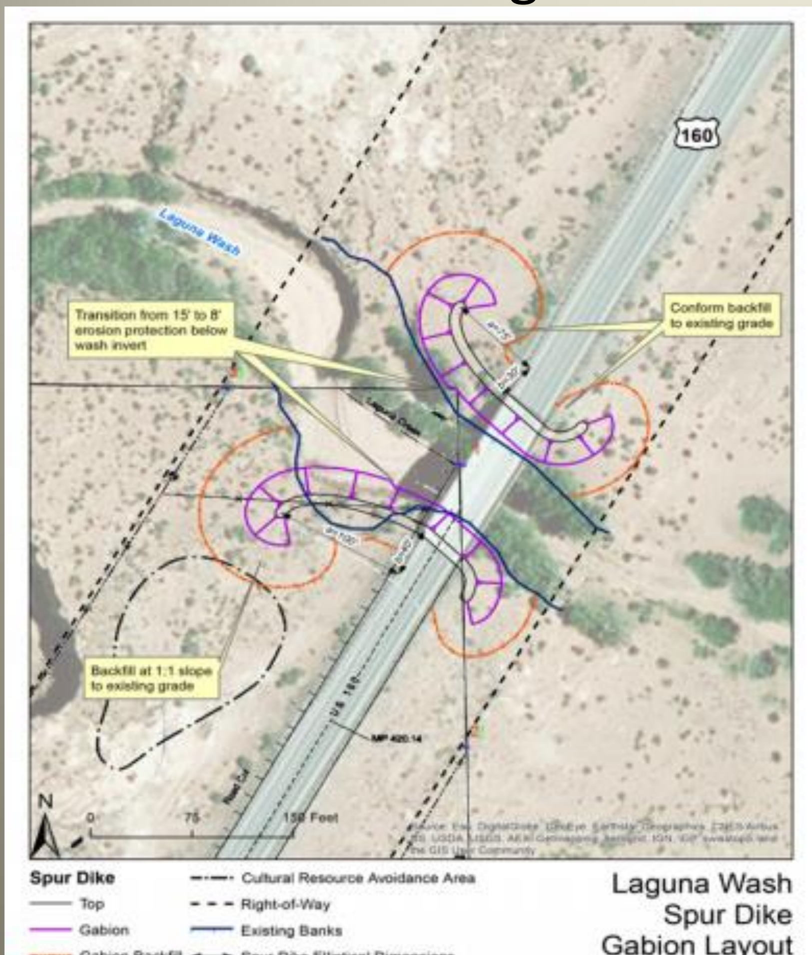
Laguna Creek Pilot Project Reach Monitoring:

- Rapid deployment stream gage
- Surface velocity radar sensor
- Particle tracking video cameras
- Indirect discharge measurements
- Repeat LiDAR scans of bridge structure and surrounding channel
- sUAS (drone) survey



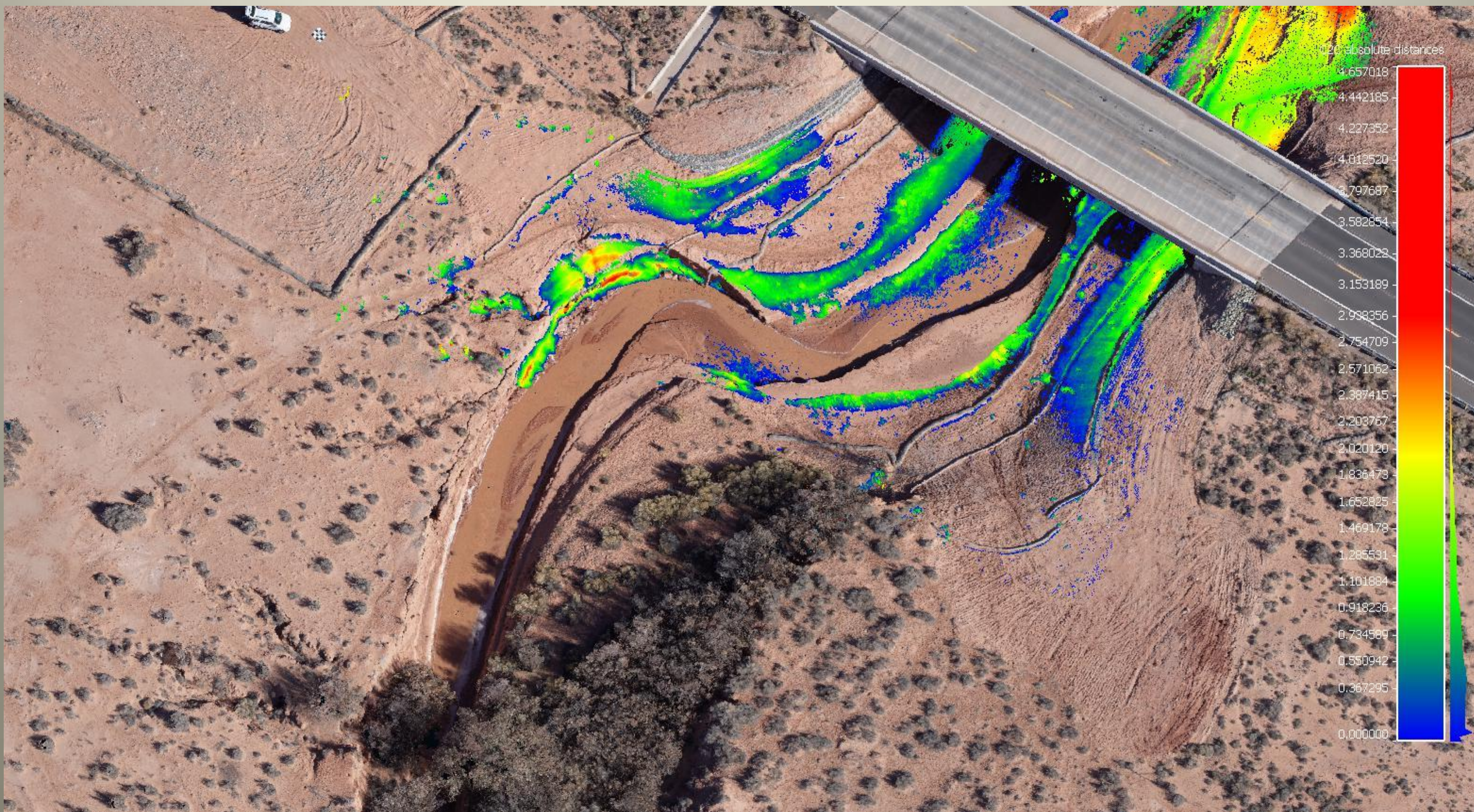
Resilience Building Example #2

State Route 160 - Laguna Creek Bridge – Dennehotso, AZ



Post Construction Monitoring Process

Post Construction Monitoring Process



2-D Erosion Change Detection Mapping

Post Construction Monitoring Process

USGS Drone Data Capture – On-going Monitoring - Built Condition Wash Meander / Ox-bow

Total Systems Thinking

Sustainable Infrastructure is the planning, programming, designing, constructing, operating and decommissioning of projects in a manner that ensures economic, social and environmental longevity (including natural hazard, weather and climate resilience) while concurrently advancing critical, institutional and systems thinking over the entire life cycle of the infrastructure.

Total Systems Thinking

Bhattacharya et al. 2016

CEA-TA

ADOT

A Climate Engineering Assessment for Transportation Assets (CEA-TA)
Incorporating Probabilistic Analysis into Extreme Weather and Climate Change Design Engineering

Steven Olmsted, Arizona Department of Transportation; Alan O'Connor, Trinity College Dublin; Constantine Samaras, Carnegie Mellon University;
Beatriz Martinez-Pastor, Trinity College Dublin; Lauren Cook, Carnegie Mellon University

Abstract

Transportation infrastructure is a complex system of assets required to deliver a myriad of services and functions. As fiscal constraint for the development and rehabilitation of such structures remains; and endless retrofitting continues to be cost prohibitive; new and novel approaches to long term planning and project development, engineering design, and life cycle assessment are paramount. The management of these infrastructure systems has now evolved from a decentralized, project-based focus, to one that now encompasses enterprise wide endeavors – administration, technology adoption, planning, design, construction, operations and maintenance. In addition, the expansion of risk analysis for extreme weather management and climate change adaptation has complicated the long term delivery of these complex transportation systems. At the 2015 Transportation Research Board (TRB) Annual Meeting, Session 197: *Mainstreaming Climate Change and Extreme Weather Resilience into Transportation*, the Arizona Department of Transportation (ADOT) introduced the challenge ahead for public entities to coordinate a host of known and unknown extreme weather and climate change issues. That challenge – Continue considering the balance between predictable asset deterioration curves, the sudden and unpredictable nature of extreme weather events and long term climate trends, new models for risk assessment and life cycle cost analysis, and appropriate adaptation strategies. This multiple part challenge necessitated a new end-to-end engineering approach to incorporate such current and future risks. At the 2016 Annual Meeting ADOT submitted a paper representing the core of that new approach – a Resilience Program and an ADOT/United States Geological Survey Partnership. That paper was graciously recognized as a best paper by the TRB Special Task Force on Climate Change and Energy. In the spirit of continuing that forward progress – this paper presents the remaining parts needed to develop a new end-to-end engineering-based asset adaption process – a structured sequence to incorporate extreme weather and climate change adaptation into the design engineering process. The paper benefits from preeminent researchers in the two integral, and practice ready, remaining parts – probabilistic modeling for engineering design and infrastructure system design life cycle outcomes for extreme weather and climate change in a transportation engineering setting.

Arizona DOT Resilience Program

Transportation infrastructure is a complex system of assets required to deliver a myriad of services and functions. The expansion of risk development for extreme weather management and climate change adaptation has complicated the long term delivery of these complex transportation systems.
In order to develop an innovative approach, the first step was to create a system process that allowed for a shift from a deterministic preset design parameter and/or frequency basis, statistical risk of failure, and historic project and programs budgeting focus – i.e. extreme events not considered – to a probabilistic analysis approach that inputs additional data, vulnerabilities, and considerations not previously considered. In 2015 and 2016 ADOT focused on linking scientific evidence-driven data capture with the design engineering processes through the development of a partnership with the United States Geological Society (USGS). Extensive 2-D/3-D engineered modeling underway.

(CEA-TA) – A Structured Sequence

Identify EX W & CC project and program candidates - *Vulnerability Assessment*

2015 FHWA Pilot Project - The study examined baseline (historical) and potential future extreme weather conditions, focusing on temperature and precipitation variables. Two future analysis periods were selected: 2025 to 2055 (referred to subsequently as 2040, the median year), which reflects the time horizon of ongoing long-range planning efforts, and 2065 to 2095 (2080), roughly associated with the expected design lifespans of some critical infrastructure types, such as bridges. To provide a long term baseline against which to compare the projections, the team also examined temperature and precipitation observations from 1950 through 1999. The report was issued by FHWA in the Spring of 2016.

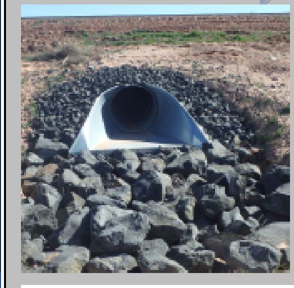
WHY IS MOVING TO A PROBABILISTIC APPROACH EVEN NEEDED?

This question could cover pages and pages. The short answer is easy. In addition to sustainable transportation attributes, there is growing consensus that if transportation systems are going to incorporate extreme weather and climate change, consideration must be developed that account for hydrometeorology/climatology, hydrology, hydraulics, and hydrodynamics. Since all these areas continue to adopt advanced mathematical modeling approaches, it is therefore logical that transportation systems and projects develop also incorporate these progressions.

Develop economic analysis process - *Justification*

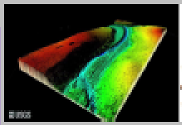
An economic analysis for the CEA-TA process would consist of using a probabilistic approach to life cycle cost analysis. The life cycle cost of an infrastructure asset such as a roadway or bridge, is the total cost to an agency throughout the asset's useful life. This includes the planning, design, construction, maintenance and decommissioning phases of infrastructure delivery. State DOTs typically initially approach this process without considering risk and uncertainty that future conditions will be different from the past, and assume a uniform distribution of annual maintenance costs and major reinvestment intervals. Long-lived infrastructure must perform under future climate conditions and climate-influenced usage that deviates from the historical data now populating infrastructure economic analysis and asset management models. Climate change impacts, such as sea-level rise, storm surges, changes in precipitation, hotter temperatures, and others are potential vectors of infrastructure failure and should be taken into consideration in infrastructure economic analysis and asset management models.

Resilience Program
Economic Analysis Pilot
US 191 MP 436 to Chinle
PROJECT NO. 191 AP 436 H8676 01 C
FEDERAL AID NO. STP-191-E(214)T
Apache County
Holbrook District



Design probabilistic modeling approach to produce an array of results - *Quality Control*

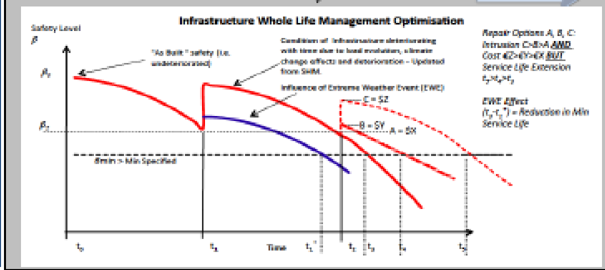
Optimize operation and maintenance of an increasingly aging stock, which is subjected to evolving loads (e.g. both live loading and climate induced loading). In response to this challenge the past decade has seen increased interest by infrastructure owners and managers in the use of probabilistic methods for the assessment/management of their assets. Employed once a deterministic assessment has rendered a repair/rehabilitate/replace now scenario



Define limits of simulation runs that incorporates latest science/engineering - *Policy*

Climate models can provide insight into future conditions, projecting air temperature, precipitation, evapotranspiration, and other factors of interest to engineers, at various temporal and spatial resolutions. However, there is a considerable disparity in the outputs provided from climate models for impacts analyses and the inputs needed by engineers for planning and design. These discrepancies include mismatches in temporal and spatial scales, complicated data extraction and preparation requirements, sizeable model, data, and scenario uncertainties, and a lack of direction for the rigorous selection of models for use in different engineering applications.
Innovative change examples:

- Every Day Counts – 4 : Collaborative Hydraulics: Advancing to the Next Generation of Engineering (CHANGE)
- NCHRP 15-61 - Applying Climate Change Information to Hydrologic and Hydraulic Design of Transportation Infrastructure
- NCAR - *The Future Intensification of Hourly Precipitation Extremes* - Andreas F. Prein et al. December 2016
- LiDAR, UAS/UAV, 2-D water modeling, 3-D visualization and animation tools
- Translational organizations to provide rigorous standards for interpretation of climate data, development of a single, simplified user interface that accesses all downscaled data sources, and tools that automatically post-process data based on defined standards



Systematically record location and resilience efforts GIS/TAMP - *Risk Management*

ADOT has been systematically capturing data sets for extreme weather and climate change use through an extensive geographic information system (GIS) effort that will subsequently support ADOT's transportation asset management planning (TAMP). ADOT's studies showed concerns with the climate and extreme weather vulnerability of bridges, culverts, pavement, and roadside vegetation / stabilization. Legislation - Focus in MAP-21 on performance based management and risk-based asset management plans; Inclusion of "resilience" in FAST Act.

Develop life cycle models to monitor investment - *BCA/ROI*

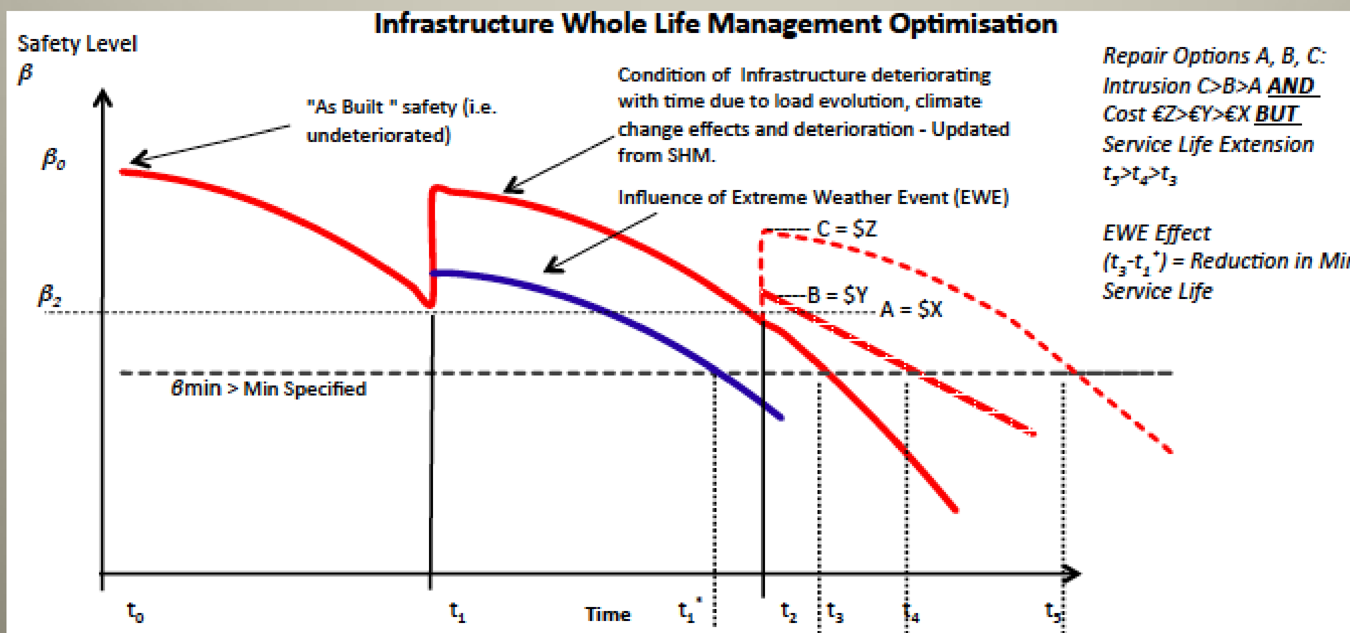
Civil infrastructure systems are among the largest local, state and Federal investments, and these infrastructure systems are critical to U.S. economic, environmental and social outcomes. Yet longstanding underinvestment in infrastructure has resulted in the poor condition of much of U.S. infrastructure, with an estimated $3.6 trillion of re-investment needed by 2020. New methods for benefit cost analysis, return on investment studies, and major rehabilitation timeline analyses are needed that incorporate probabilistic approaches, and minimize regret by DOTs under a changing climate. The results of CEA-TA provides that method.

Acknowledgments

The completion of this project would not have possible without assistance from many stakeholders both within and outside ADOT that contributed to this effort. Specifically, the International Symposium - *Transportation Resilience: Adaptation to Climate Change and Extreme Weather Events*, June 16-17, 2016 at the European Commission in Brussels, Belgium that was the catalyst for the transatlantic partnering. The ADOT author wishes to acknowledge the efforts and support of: ADOT State Engineer's Office and ADOT Environmental Planning.

Design Engineering Tool

Developing bridge asset class probabilistic engineering approach that assesses the stressors inherent to the built structure itself – live loading, extreme weather loading, climate induced loading using watershed, runoff data, topo, hydraulics, bridge design, and computation of the probability of failure at the considered limit state(s)



A. O'Connor

Resilience GIS Database

Data

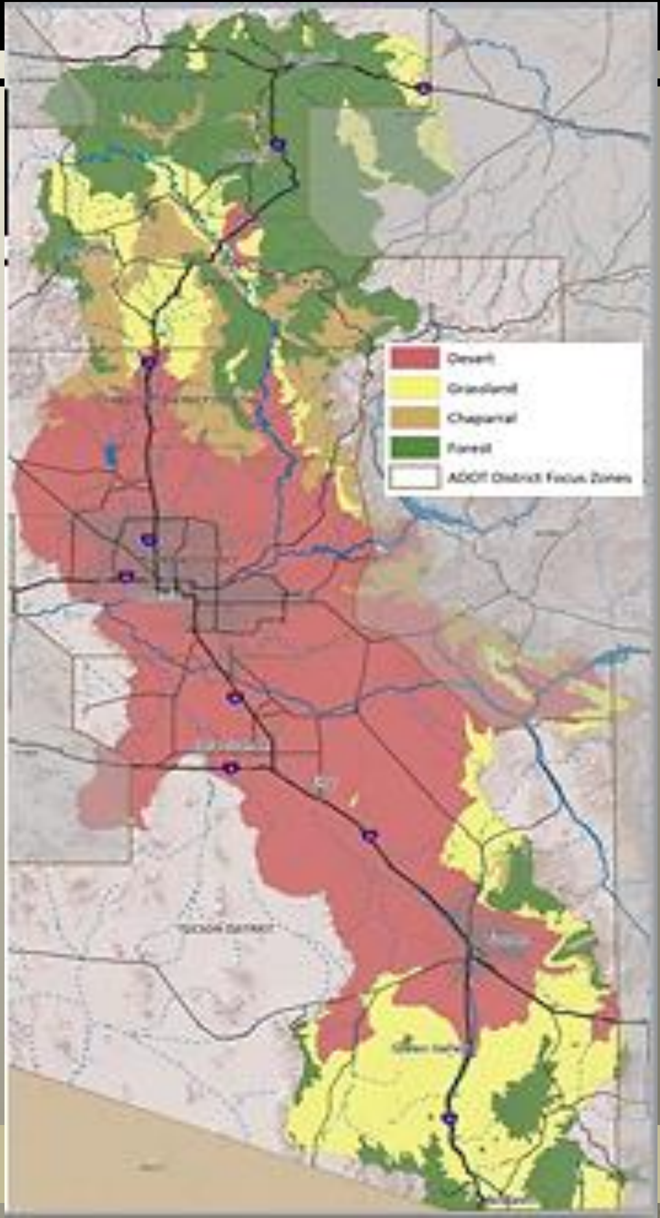
- ADOT's USGS Data
- Drought & Wildfire
- Layers from ADOT's USGS Flood map
- Dust storm data (I-10 pilot)
- 5-yr program priority project information
- Bridges (including scour program)
- Culvert
- ADOT system base layers
- Geohazard locations
- Soils
- Live Feeds

Data

- ADOT/USGS Project Work
- Resilience (Extreme Weather and Climate) Building
- Resilience Investment Economic Analysis assessment locations
- Climate Engineering Assessment for Transportation Asset (CEA-TA) locations
- Every Day Counts CHANGE 2-D modeling projects
- 2050 and 2100 climate data downscaling mapping
- Statewide drainage dashboard
- Weather event dashboards

Develop Geographic Specific Climate Models

- Large, geographically diverse study area (over 30,000 square miles)
- High spatial resolution climate data desired
- Stressors included both average and extreme temperature and precipitation
- Helpful existing tools (e.g., FHWA CMIP Processer), but customization required
- Modest resources for collection and processing



Climate Data Selection

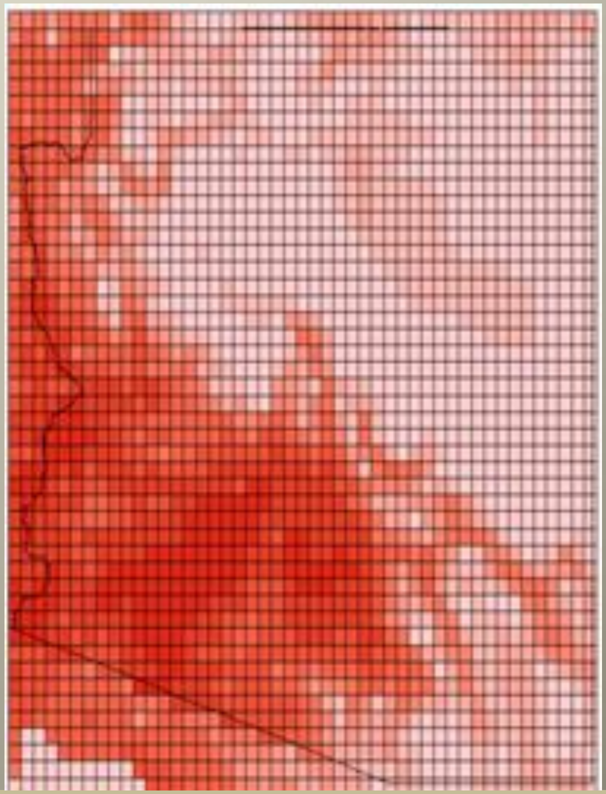
Parameter	Specification
Projections and Historical Data Source	Downscaled CMIP5 Bias Corrected Constructed Analogs (BCCA) daily projections with accompanying historical data
Emissions Pathway	Representative Concentration Pathway 8.5
Downscaled General Circulation Models (GCM)	NorESM1-M, HadGEM2-ES, CSIRO-MK3.6, CanESM2, MPI-ESM-LR, MPI-ESM-P, GFDL-ESM2M
Horizontal Spatial Resolution	1/8° (~7.5 mile or ~12km)
Temporal Resolution	Daily for 1950-2000 (backcastings from models in addition to historical data), 2025-2055, and 2065-2095
Model Outputs	Temperature (daily maximum and minimum) and precipitation (daily total)

Climate Output Metrics

Maximum 1-Day Precipitation Event (by time period)
100-/200-Year Maximum Precipitation Event using Generalized Extreme Value distribution
Minimum Annual Precipitation
Average Annual Precipitation
Average Number of Days Per Year in which Precipitation Exceeds Baseline Period's 99th-Percentile Precipitation Event
Average May-June-July-August Precipitation
Average Daily Maximum Temperature
Average Number of Days Per Year in which Temperature equals or exceeds 100 degrees
Average Number of Days Per Year in which Temperature equals or exceeds 110 degrees
Average Number of Days Per Year in which Temperature falls below or is equal to 32 degrees
Average Daily Minimum Temperature

Climate Data Outputs

- Arizona was laid out in 12 km x 12 km grid (total of 2680 grid elements)
- Grids are consistent with format of downscaled climate data
- Nineteen (19) climate models
- Considered two time periods
  - 2025-2055
  - 2065-2095



Resilience Building Example #3

Arizona Department of Transportation

Resilience Program

Project Level Natural Hazard Assessment

Phase 1 & 2 Interim Report

ADOT

Project No.: 080 CH 298 H8937 01C

Federal Aid Project No.: 080-A(212)T

Bridge Replacement: $11 million

San Pedro River Bridge Structure No. 609

State Route 80 MP 298.79

Resilience Building Example #3

Resilience Building Example #3

Phase 1 - Initial Assessment and Root Case Analysis (2019-2020)

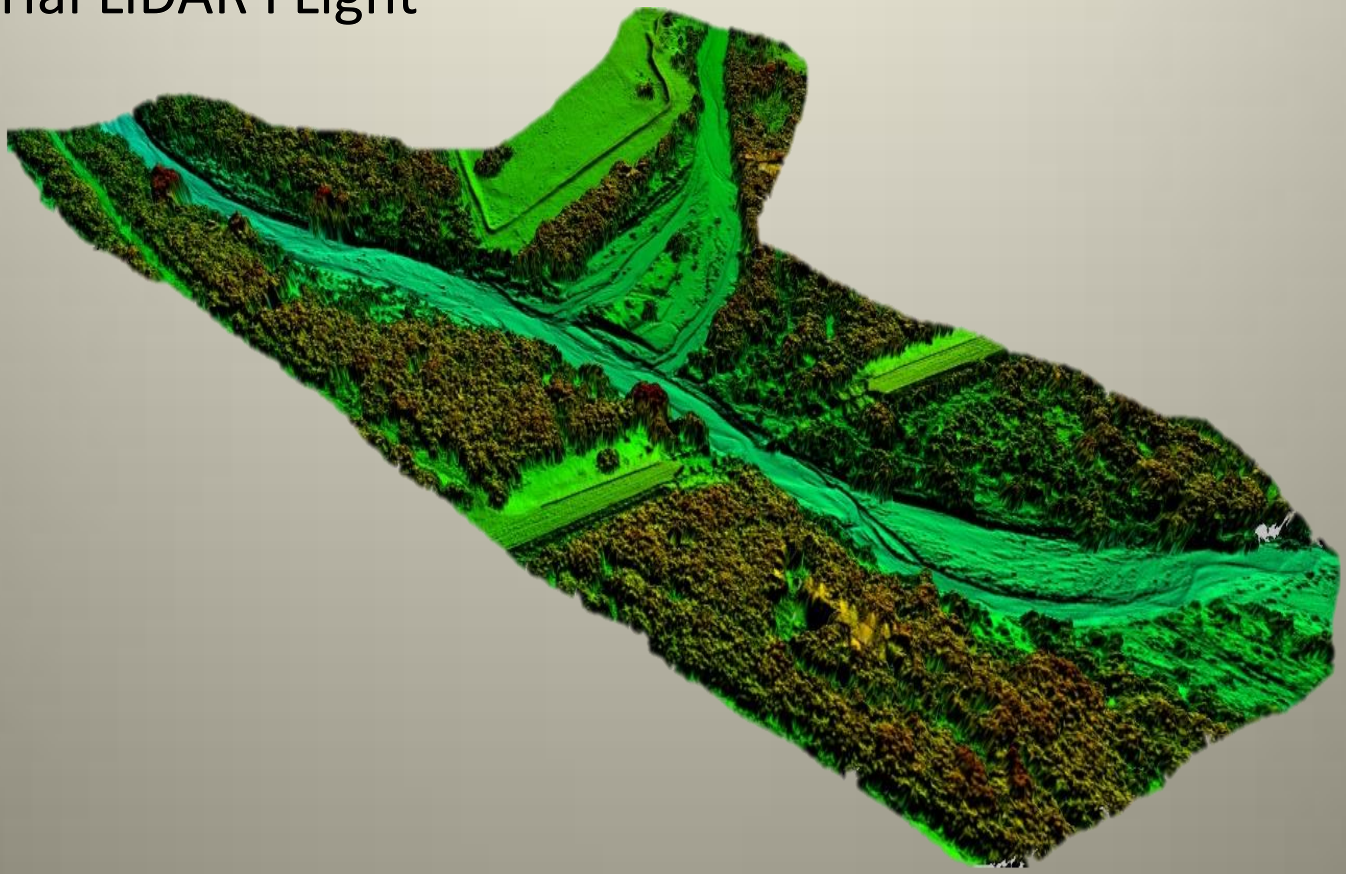
- Hydrology – 2,000 square mile watershed
- Hydraulic Engineering
- USGS Analysis
- Biotic Analysis
- Climate Analysis

Root Cause Analysis Results

The lack of historical site specific hydrology, the severe scour concerns, climate, biotic, risk of overtopping at the 50-year event, and regional risk findings it was recommended a full structural, scour, and natural hazard probabilistic risk analysis be conducted.

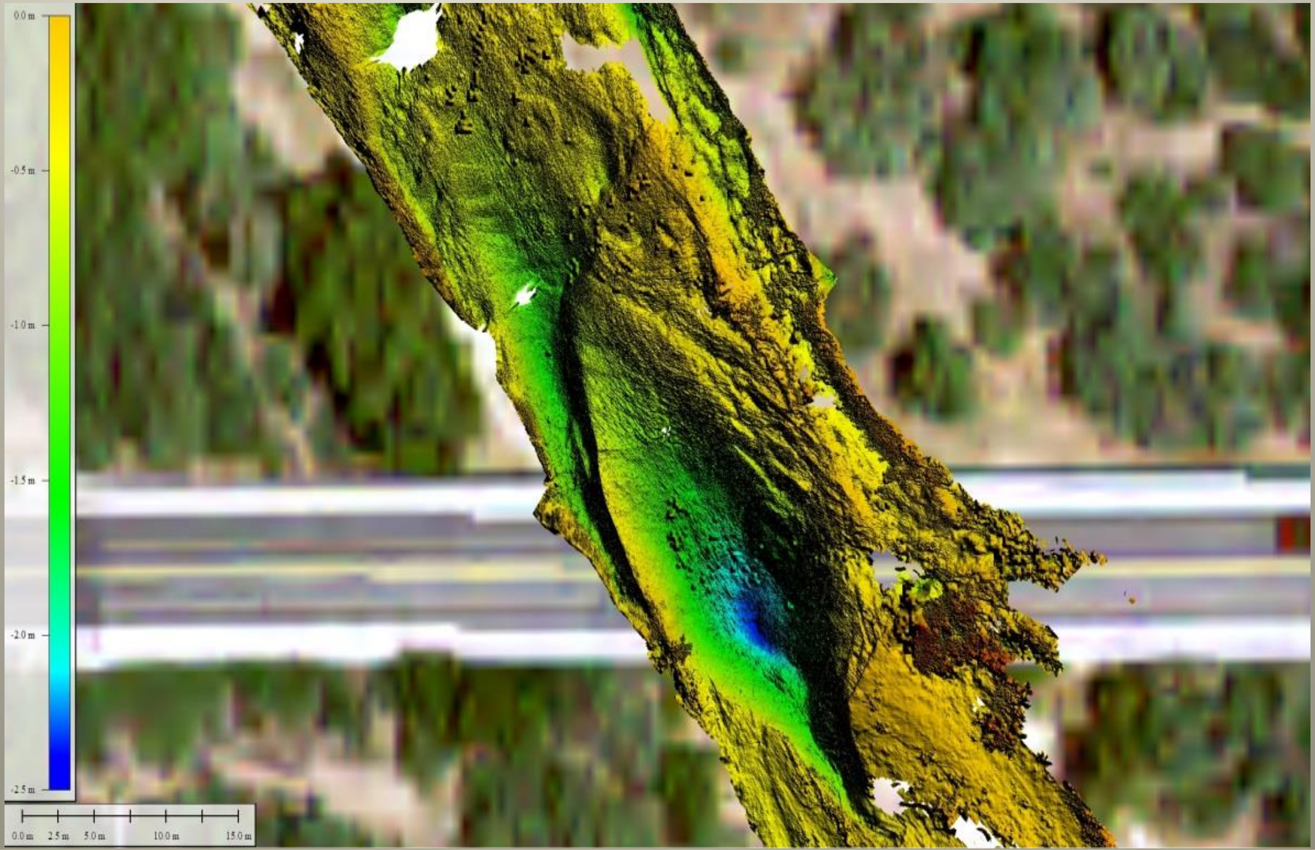
Resilience Building Example #3

Phase 2 – Probabilistic Science and Engineering Risk Analysis (2021-2022) – Aerial LiDAR FLight



Resilience Building Example #3

Phase 2 – Probabilistic Science and Engineering Risk Analysis (2021-2022) – USGS Monitoring and 2-D Modeling

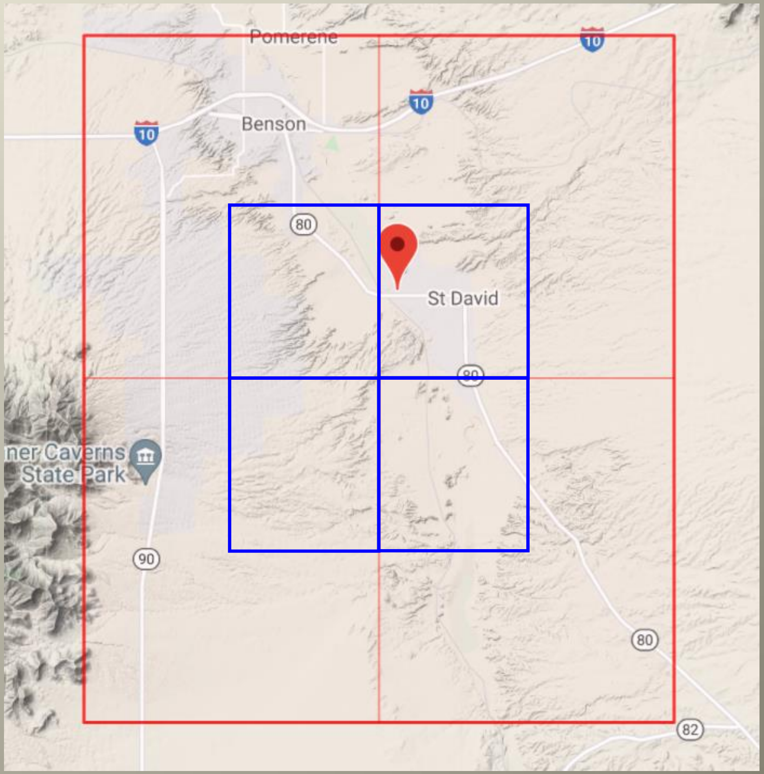


Resilience Building Example #3

Phase 2 – Probabilistic Science and Engineering Risk Analysis (2021-2022) – Updated Climate Modeling

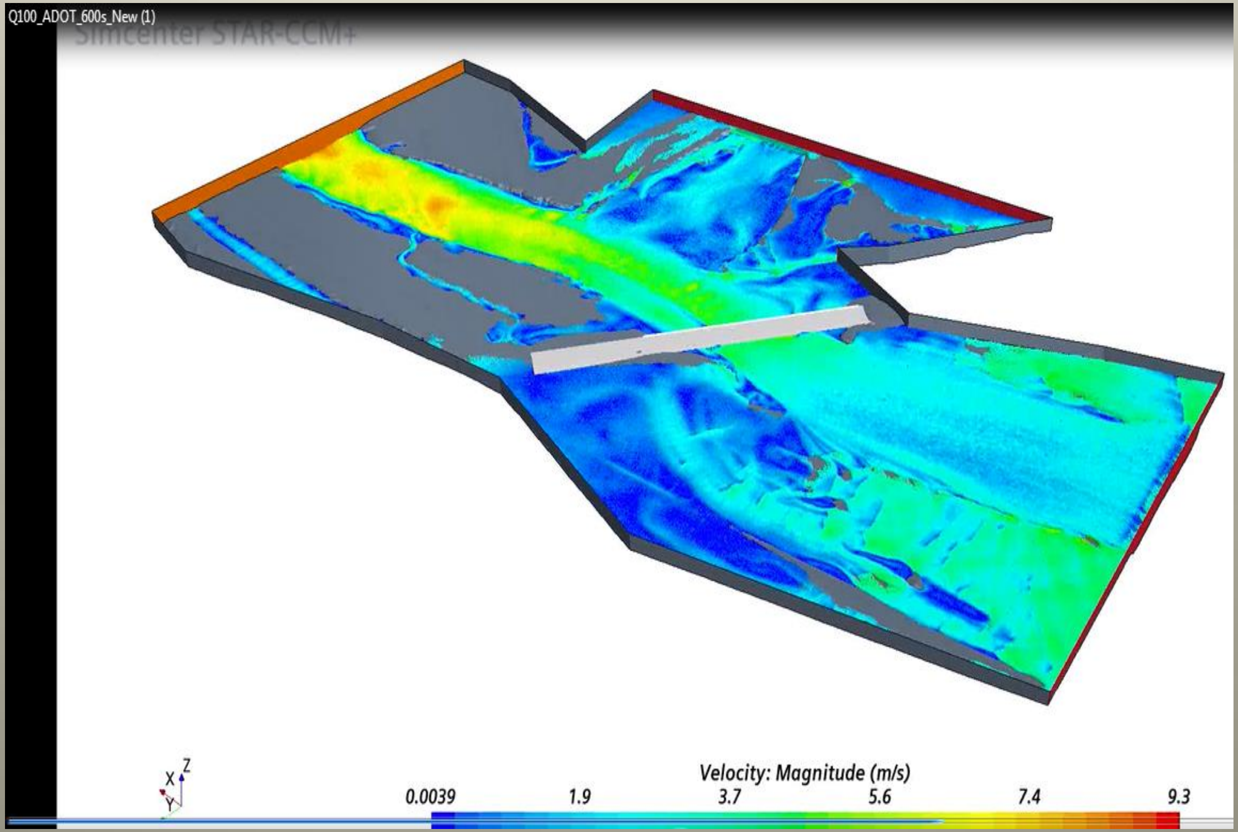
Table 2. Analysis Coordinates for Study Site

Ensemble	Grid Point	Latitude	Longitude	Distance (mi)
BCCAv2	1	31.9375	-110.3125	4.44
	2	**31.9375**	**-110.1875**	**4.25**
	3	31.8125	-110.3125	7.36
	4	31.8125	-110.1875	7.24
LOCA	1	31.90625	-110.28125	1.96
	2	31.90625	-110.21875	1.72
	3	**31.84375**	**-110.28125**	**4.58**
	4	31.84375	-110.21875	4.49



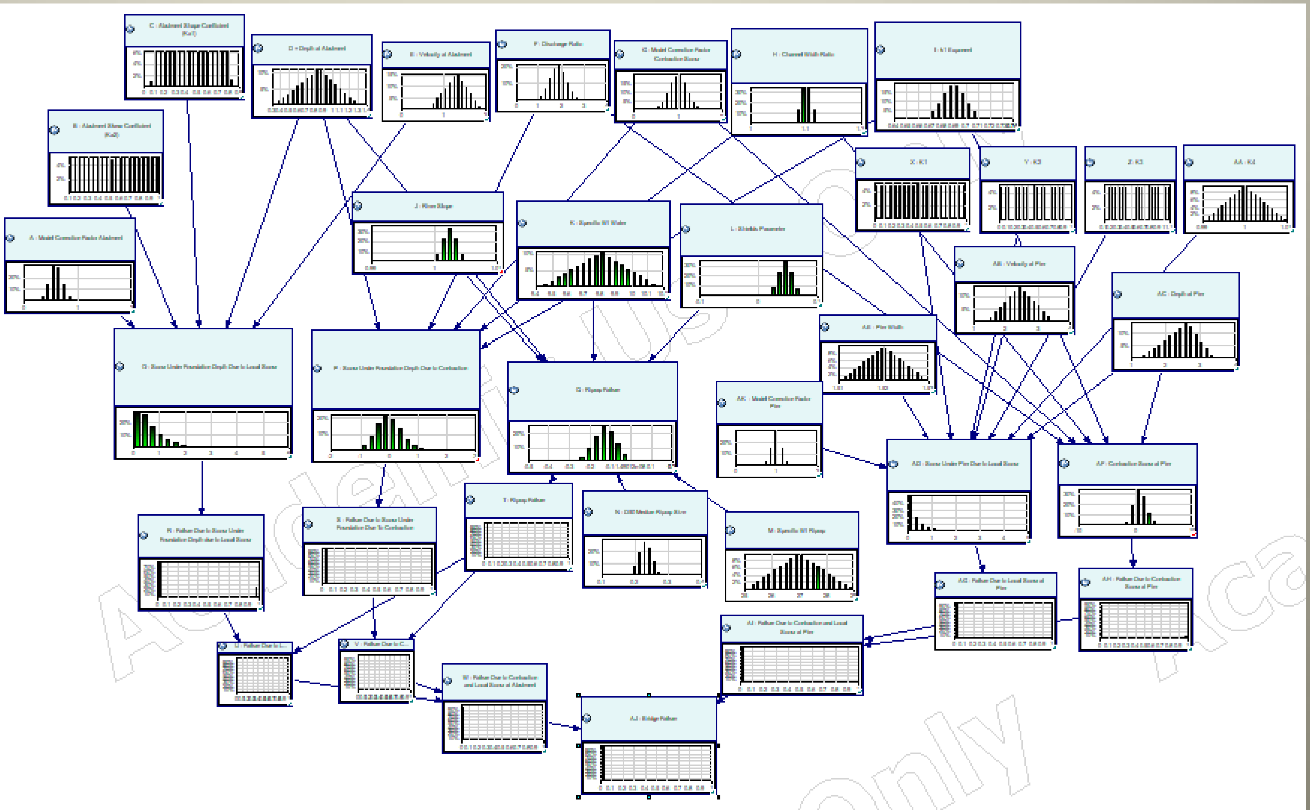
Resilience Building Example #3

Phase 2 – Probabilistic Science and Engineering Risk Analysis (2021-2022) - Computational Flow Dynamic Simulations



Resilience Building Example #3

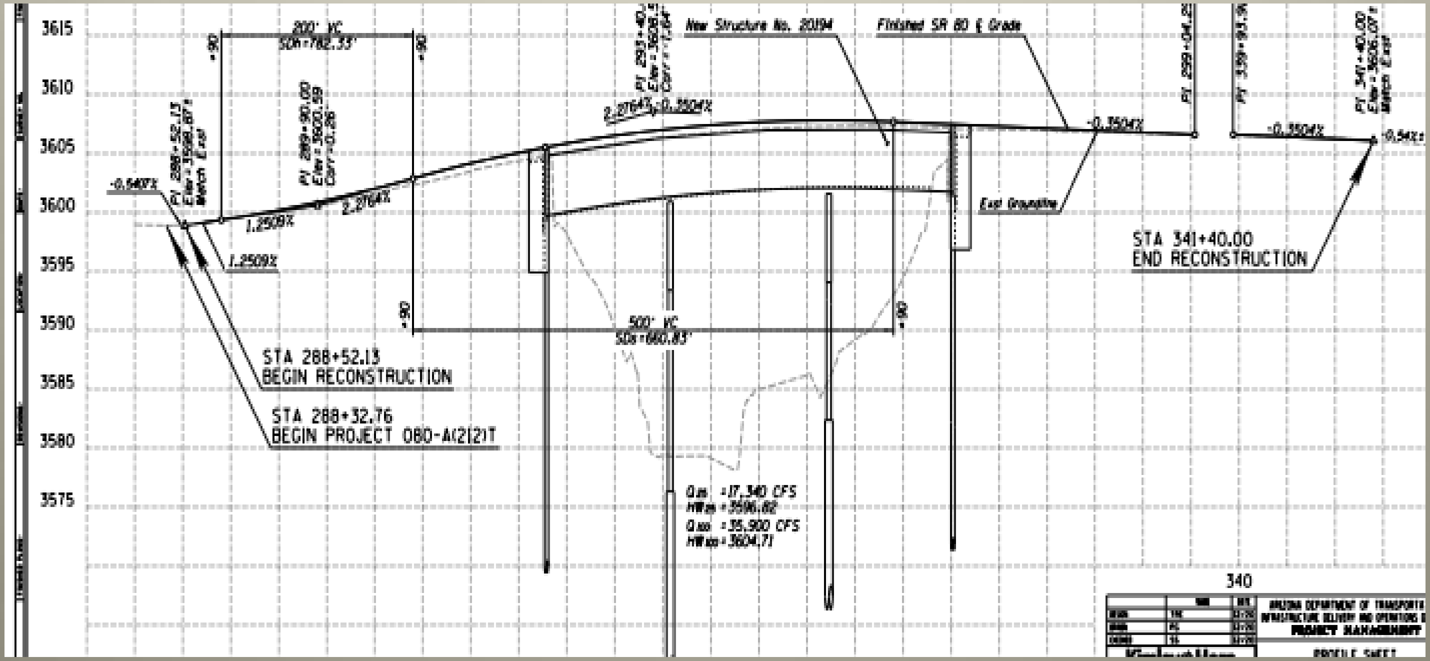
Phase 2 – Probabilistic Science and Engineering Risk Analysis (2021-2022) - system failure probability utilizing Bayesian Network (BN) Methodology



Resilience Building Example #3

Phase 2 – Phase 2 Outcomes and Design Storm and Resilience Building Changes

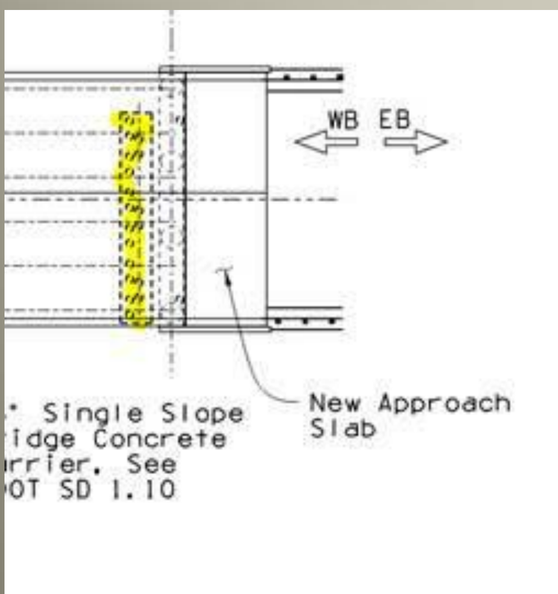
1. Reduce the number of bridge spans subject to erosion
2. Deepen the bridge's vertical supports (bridge and abutment piers)

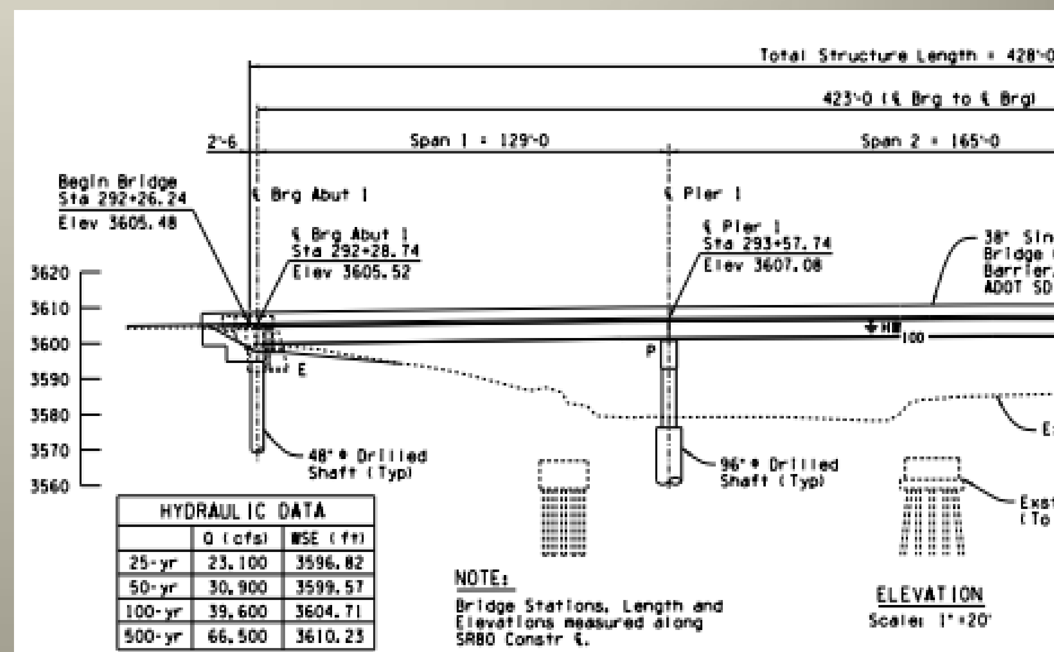


Resilience Building Example #3

Phase 2 – Phase 2 Outcomes and Design Storm and Resilience Building Changes

3. Reuse existing bridge abutments
4. Raising the bridge profile 1’





What's Next

While different methods to quantify the economic impact of weather & natural hazard for infrastructure exist, advancing resilience tools for:

- Cost benefit analysis
- Return on investment
- Risk thresholds identification (fortify – rebuild – or absorb event risk)
- Identifying specific durability limit states
- Major rehabilitation timeline analyses
- Resilience bond adoption - Improved public agency awareness

are needed that incorporate probabilistic approaches, and minimize regret by DOTs under changing extremes and climates.