Assessment of Landslide Impacts Along Oregon Lifelines

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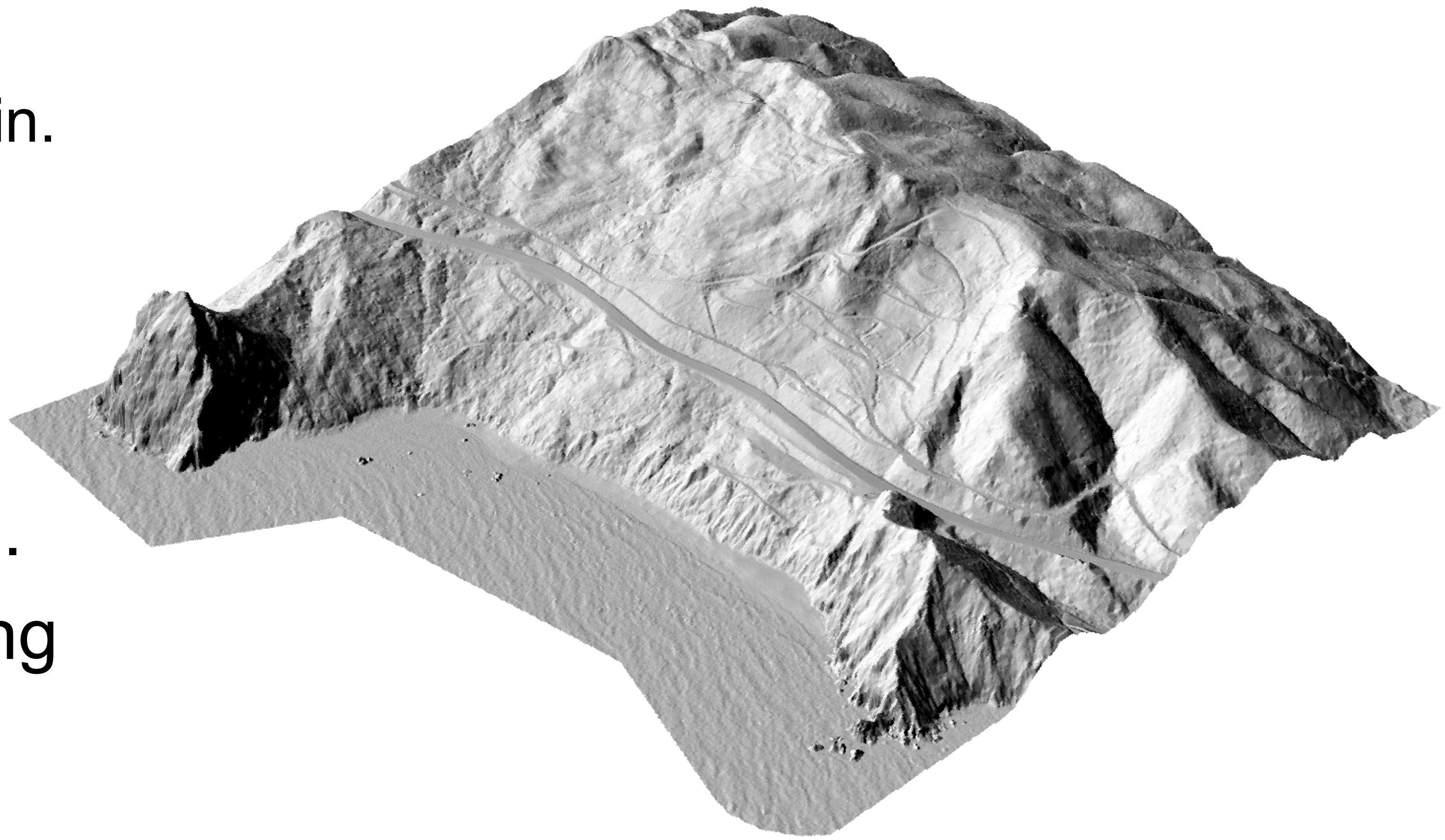
Landslides in Oregon

- Landslides are a major source of infrastructure damage in the Pacific Northwest.
- Landslides are a negative geotechnical asset; their mitigation is also an asset. Both are too often forgotten…
- Avoiding or absorbing damage in geotechnical assets achieved through:
  - Expanded attention to monitoring
  - Cataloguing landslides and assets for analysis
  - Using advanced in-situ and remotely-sensed data to interpret landforms
  - Using data-driven models to understand landslide impacts
- Overview of a climate- and seismic-focused project focused on landslide impacts.

Lidar as an asset.

- Detailed topography for:
  - Stability analyses.
  - Identification of unstable terrain.
  - High-resolution change.
- Can be integrated with geospatial information about infrastructure, development, homes, population and more.
- Particularly useful for mapping past landslide features.
- ***Great!!! … Now what?***

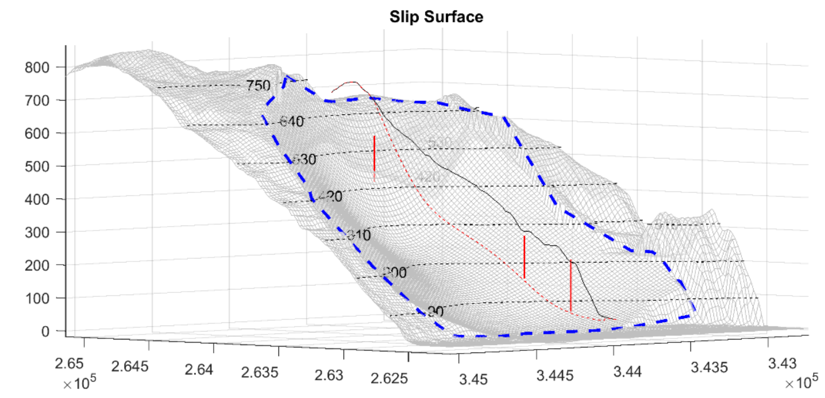


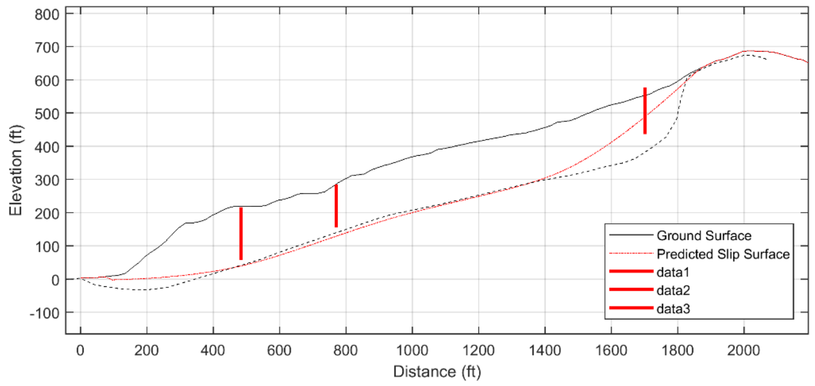
Back-Analyses of Landslides

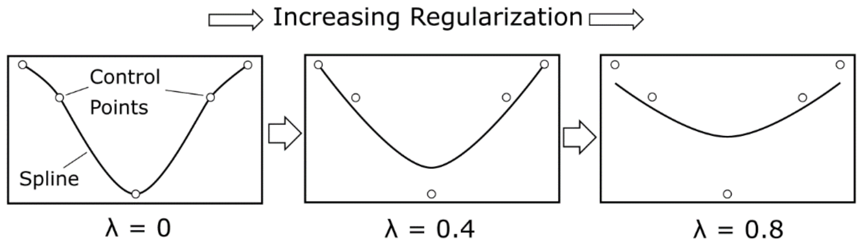
- Lidar DTMs very applicable to interpreting singular events.
- Through sensitivity analyses and use of landslide inventories, we can explore regional trends in landslide characteristics.
- Herein, we introduce an approach to:
    - Infer landslide slip surface geometry for entire landslide inventories
    - Reconstruct pre-failure topography for landslides
    - Perform 3D back-analyses on thousands of landslides
    - Infer spatial trends of strength associated with specific geologies, regions, materials, etc.

Hybrid Thin-Plate Spline

- We leverage high-resolution lidar topographic data to analyze these large datasets.
- We use a modified thin-plate spline (TPS) to use main scarps, landslide deposits to infer rupture surface geometry (Bunn et al. 2020).
- TPS capable of producing complex shapes found in landslide slip surfaces.
- TPS may reduce complexity through regularization of boundary conditions.







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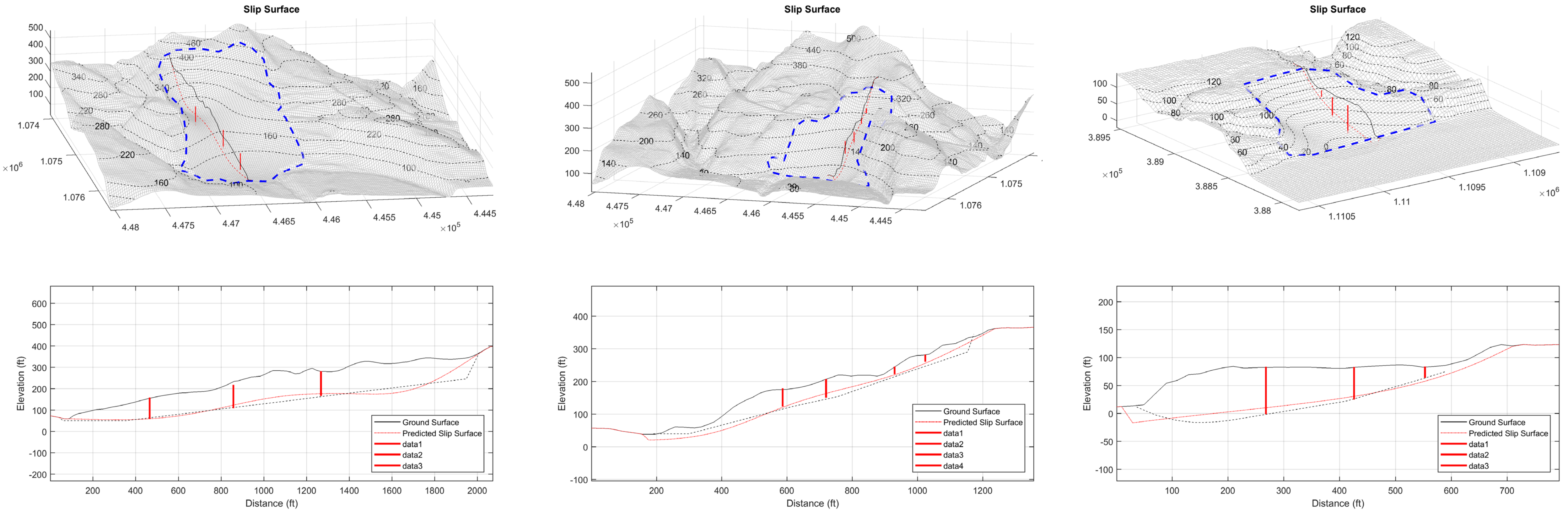
Alberti, S., Leshchinsky, B., Roering, J., Perkins, J., & Olsen, M. J. (2022). Inversions of landslide strength as a proxy for subsurface weathering. *Nature Communications*, *13*(1), 6049.

- Applied to series of well-characterized landslides to calibrate regularization, resolution, projection constraints.



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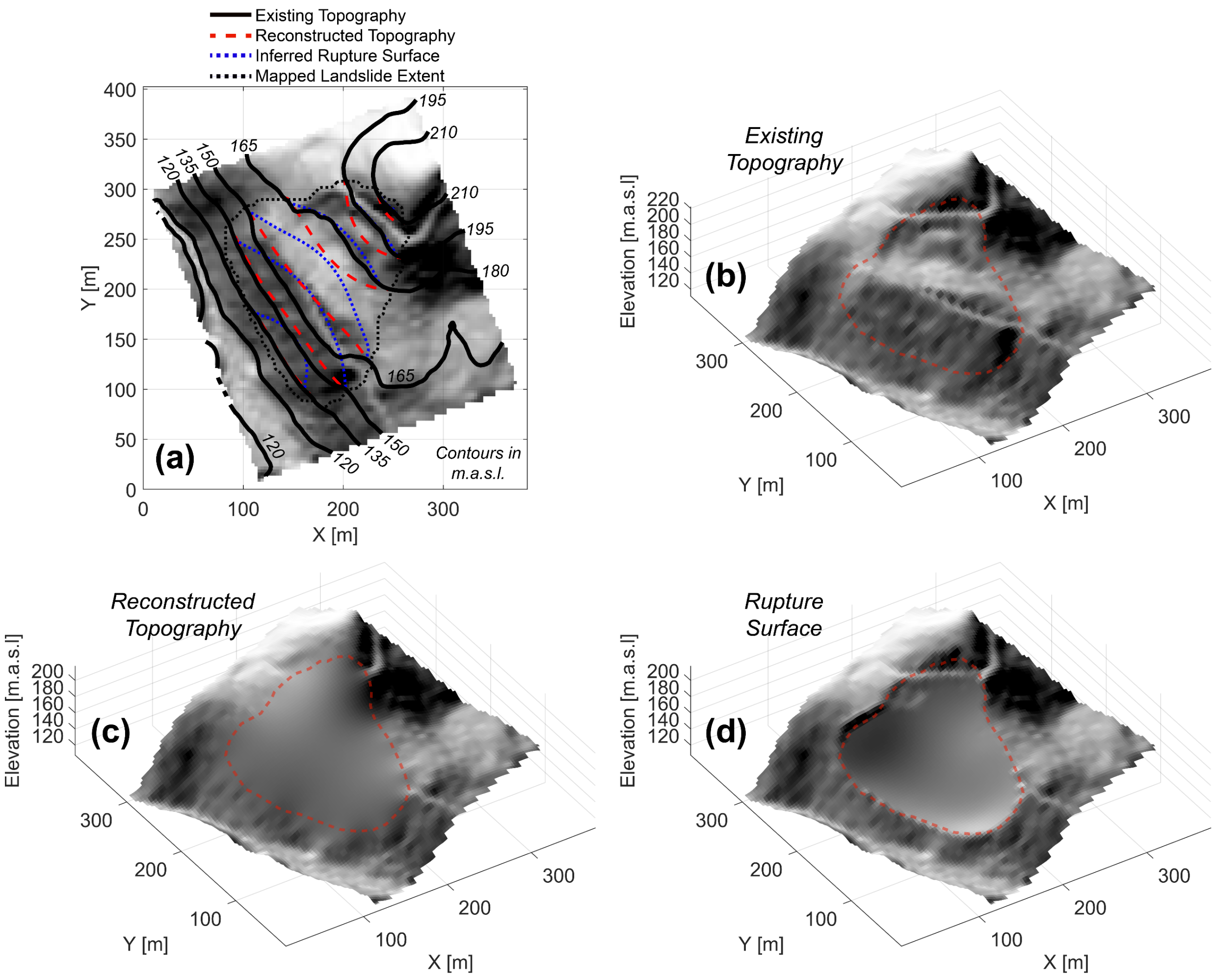
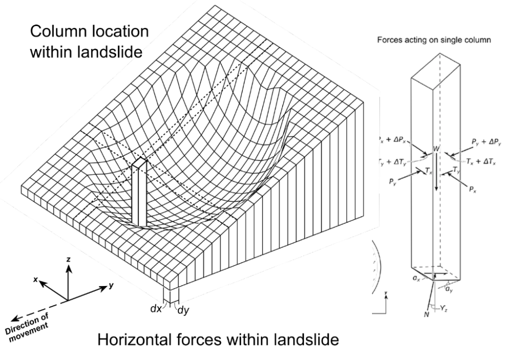
Reconstruction of Surface Geometry

- Similar procedures may also be applied to reconstruct pre-failure surface geometry.
- Done through ignoring landslide extents and infilling from surrounding “unfailed” terrain.





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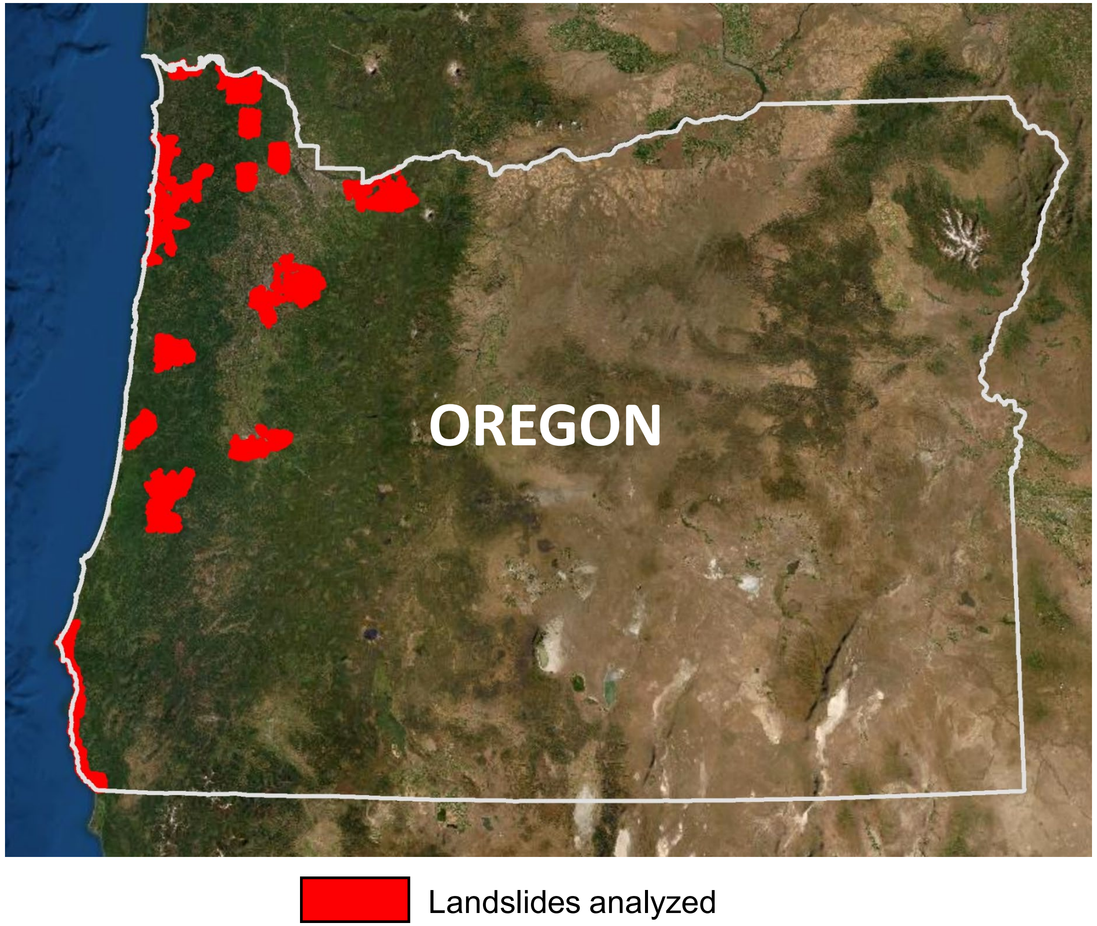
Application to Landslide Inventories

- We gathered high-quality landslide inventories in Oregon (DOGAMI SLIDO).
- Reconstruct failure geometries from each inventory to glean trends in geologic unit, geometry, mechanism, strength.
- Performed on landslides w/ limited estimated evacuation.
- Overall, we used >7,300 landslides in our analysis.



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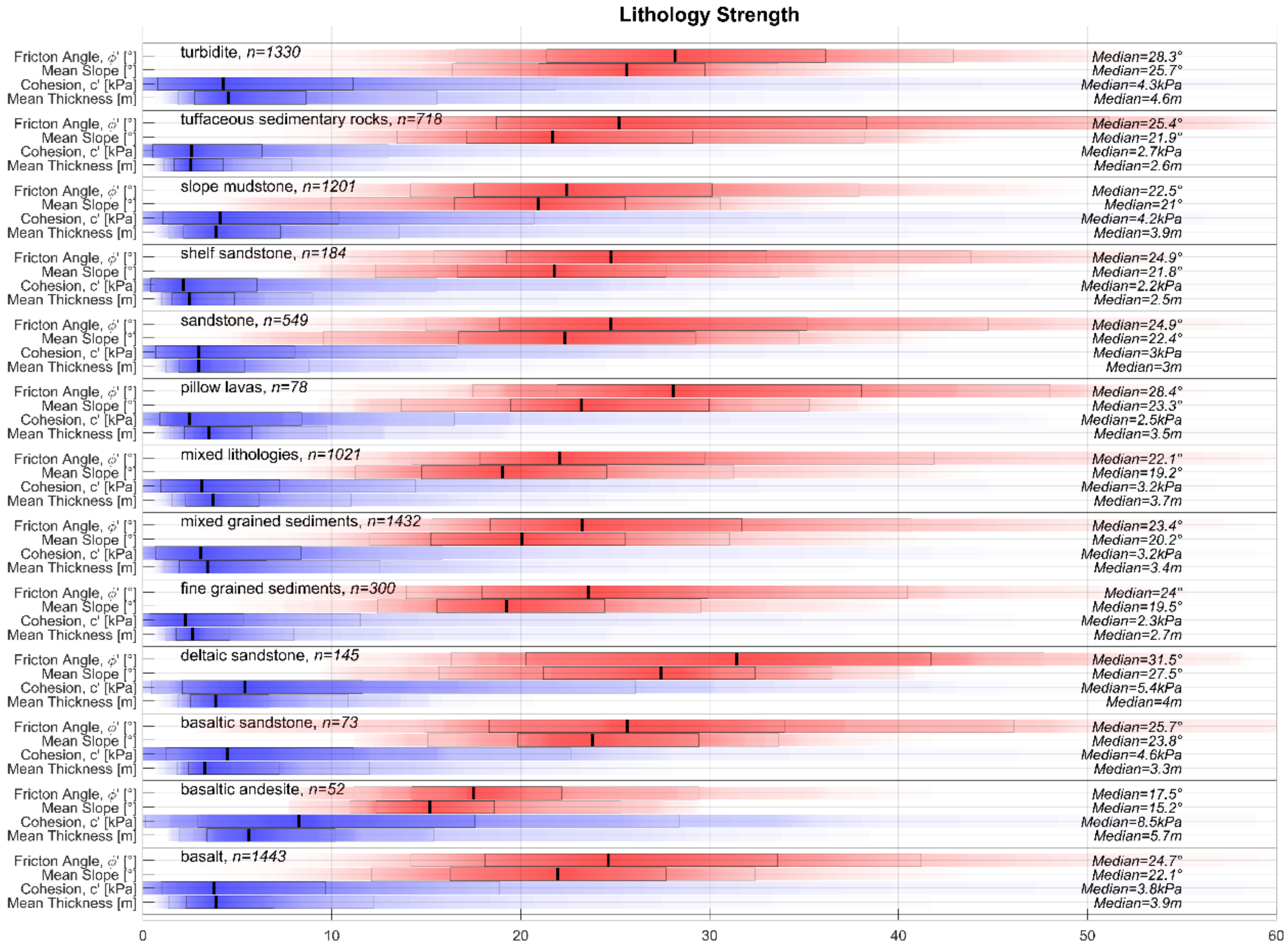
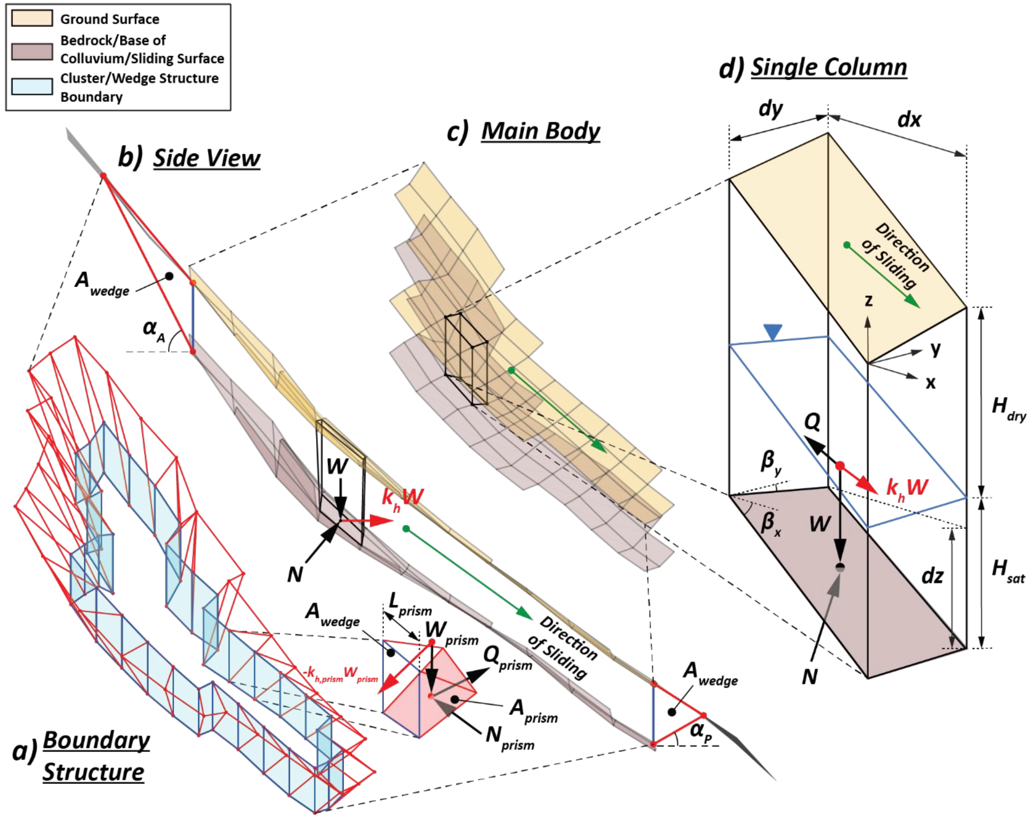
Lithology

- Can take geologic classifications and have associated strength properties!
- Can take typical lithologic units and begin to characterize differences in strength, morphology, etc.
- **Can be used in forward-facing models!**



Landslide Susceptibility and Risk

- We can apply slope stability models as a predictive tool for shallow landslide susceptibility.
- Use lidar-derived digital terrain models, forensic inputs, remotely-sensed soil moisture data.
- Physics- and process-based approach enables extrapolation to a variety of triggering disturbances, e.g.:
  - Storm intensity (intensity-duration-frequency relationships).
  - Seismic forcing.
- Evaluate role of antecedent ground moisture, rainfall anomaly, earthquake timing on landsliding.

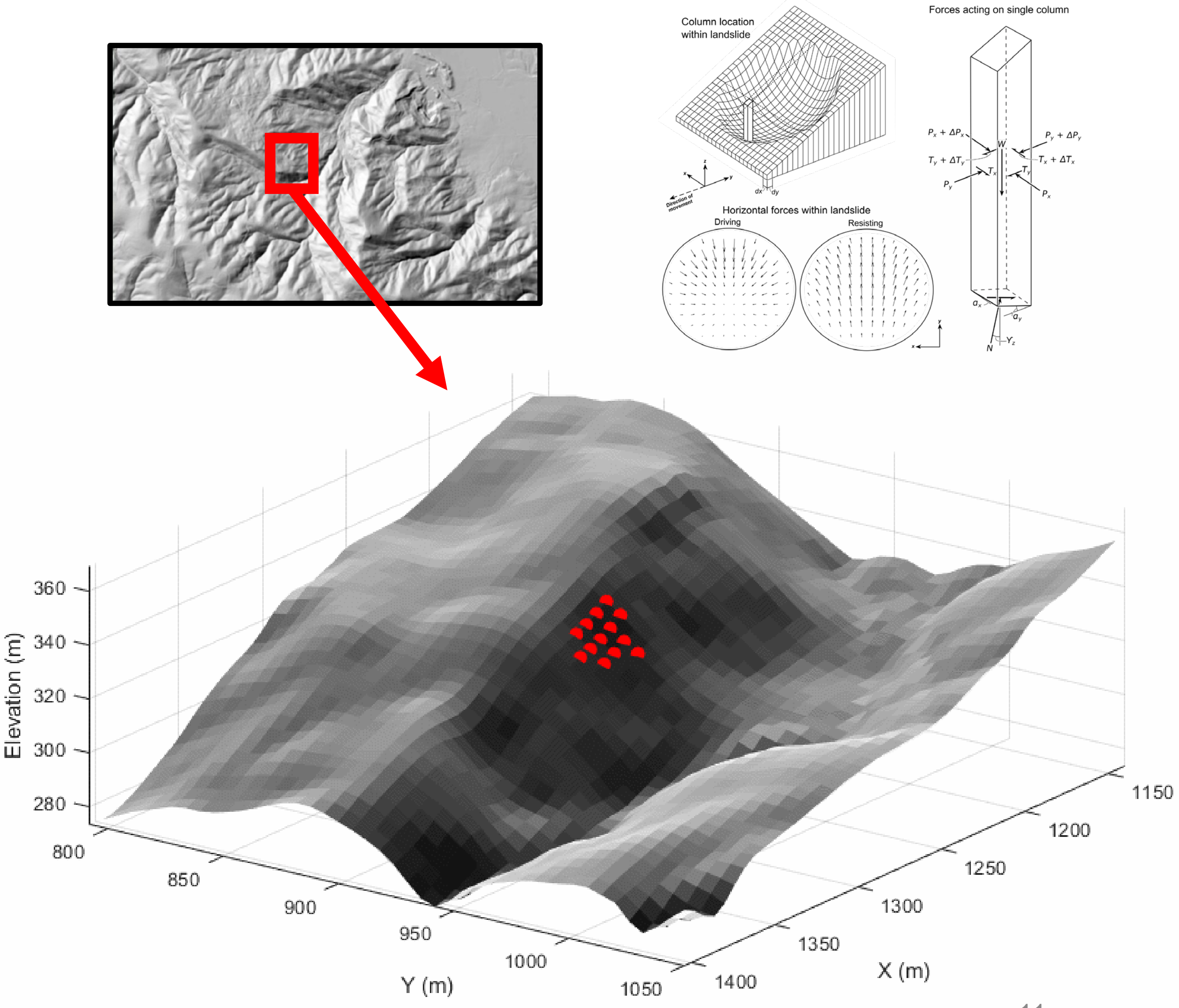


Susceptibility

1) Characterizes discrete landslide volumes – triggered by rainfall or earthquakes

2) Identify unstable clusters using 3D limit equilibrium

3) Achieve force equilibrium by accumulating downslope cells of soil



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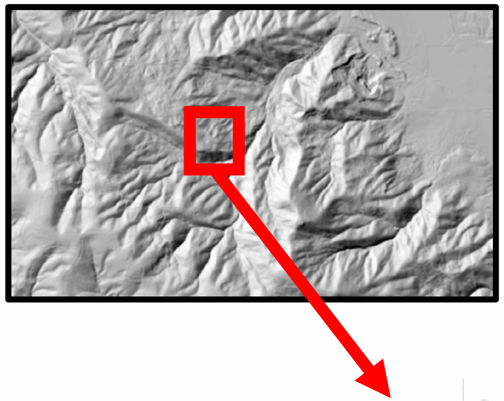
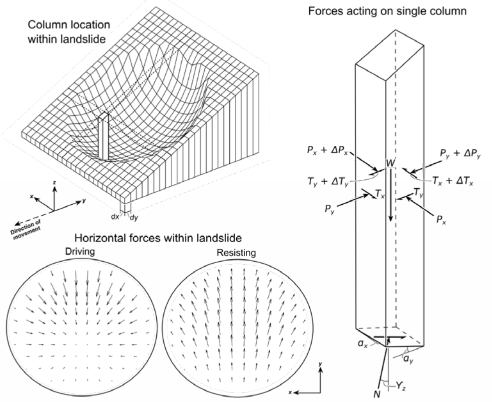
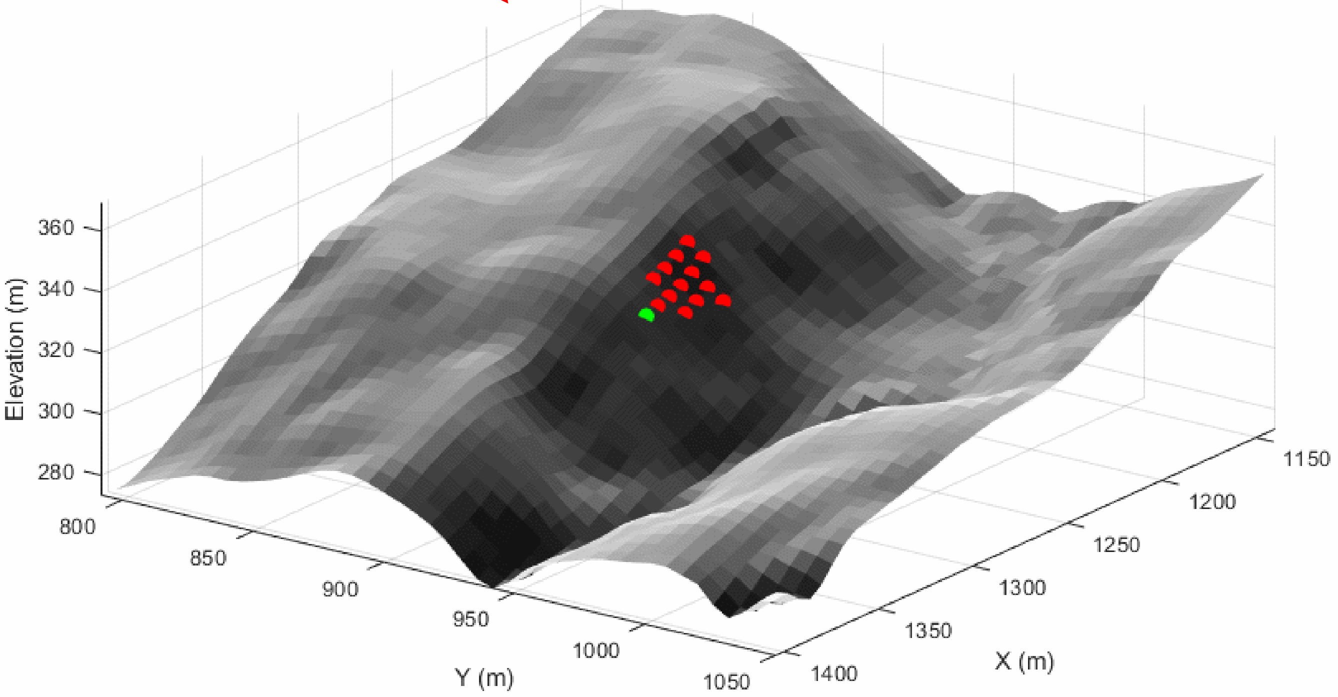
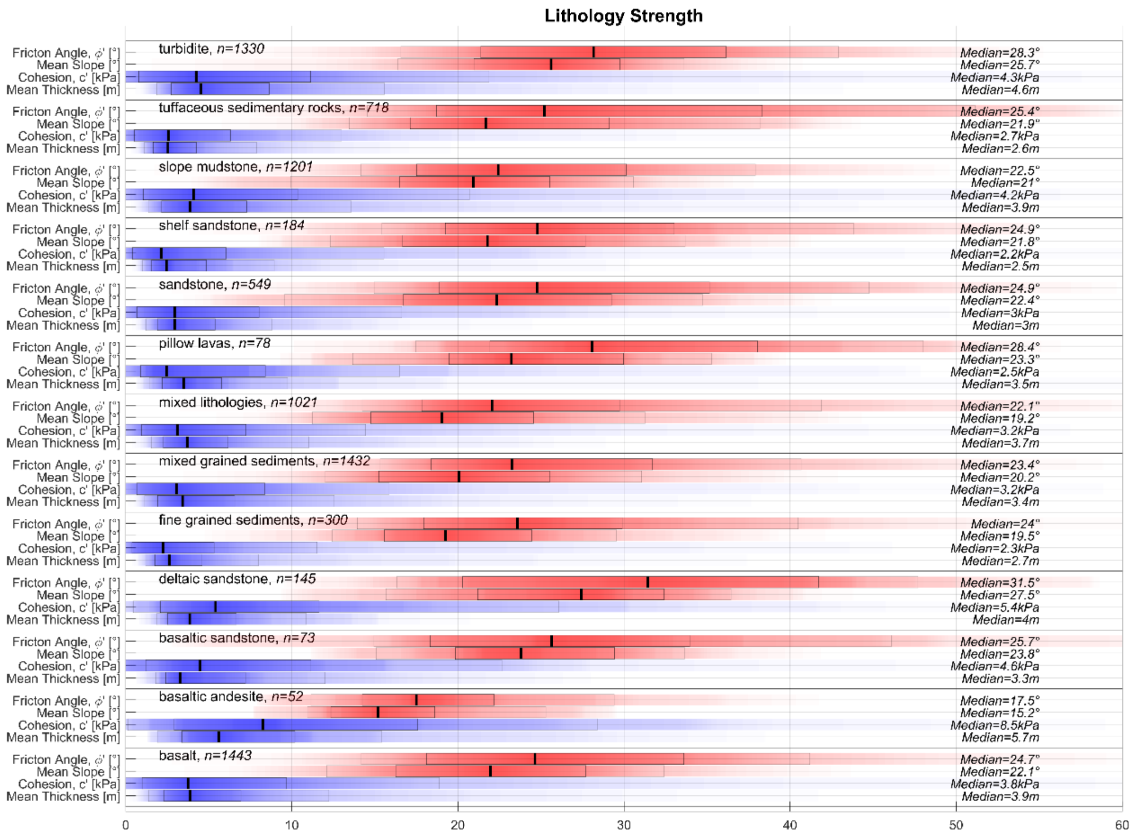






Inputs

- Strength
  - Distribution determined from forensics code.
- Soil Moisture, Unsaturated Properties
  - Soil moisture time series from NASA SMAP satellite data (daily)
  - SoilGrids, Rosetta GeoTransfer Function
- Estimated Soil Depth
  - Roering (2006) hillslope evolution model
- High-resolution DTM
  - OLC 3 ft. lidar, 1068 km^2
- Intensity-duration precipitation for storm recurrence interval
  - ODOT hydraulics manual (e.g. 10 year storm)
- Seismic Event PGA map
  - OHELP, (Sharifi et al. 2016)



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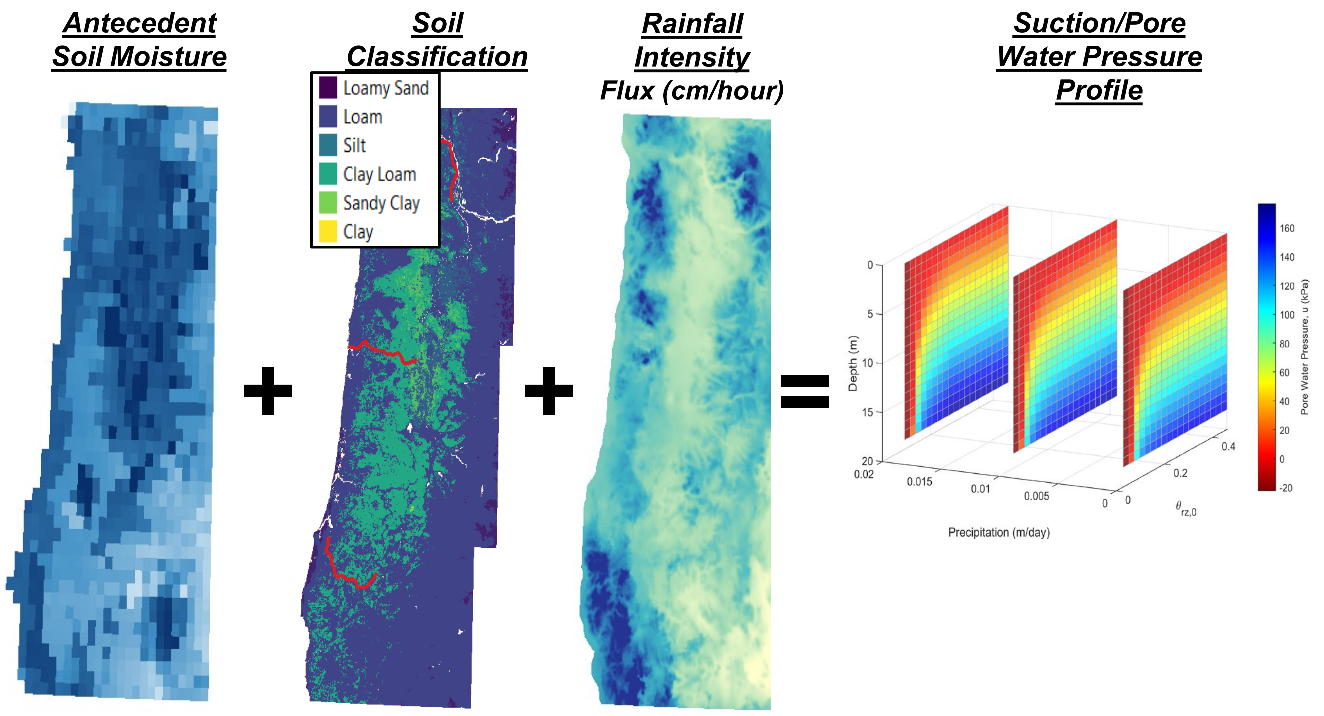

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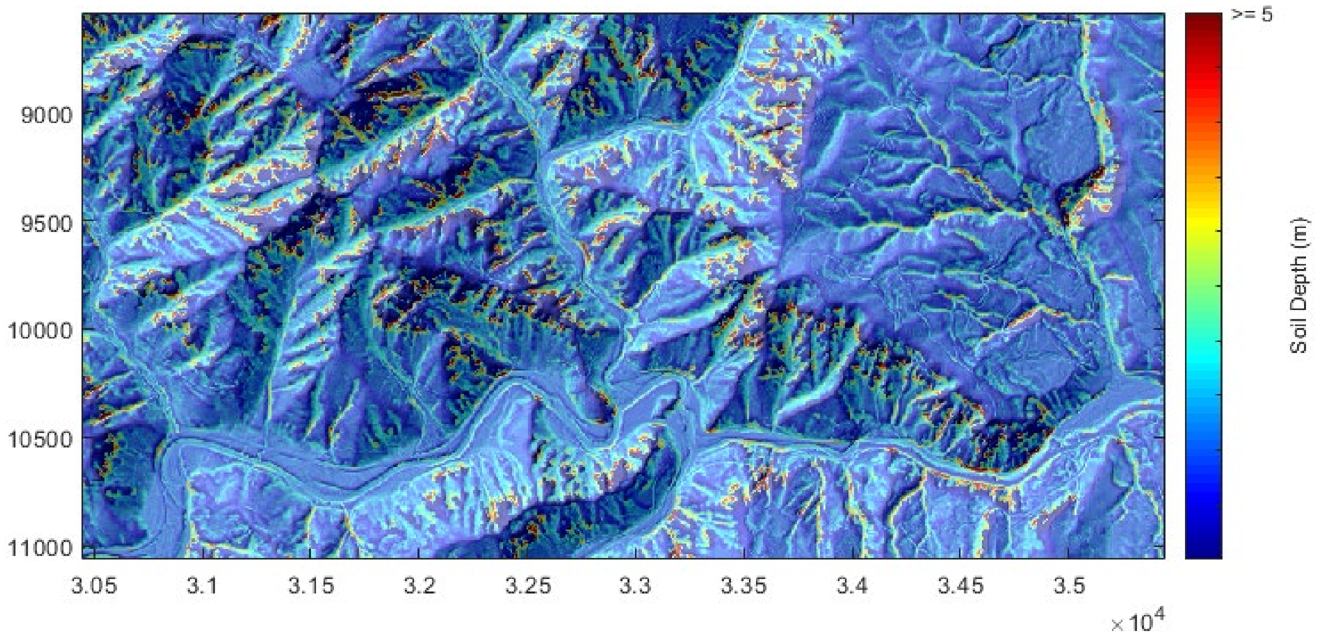

Thinner soil mantle in high curvature areas helps constrain landslides to faces and typical areas of instability

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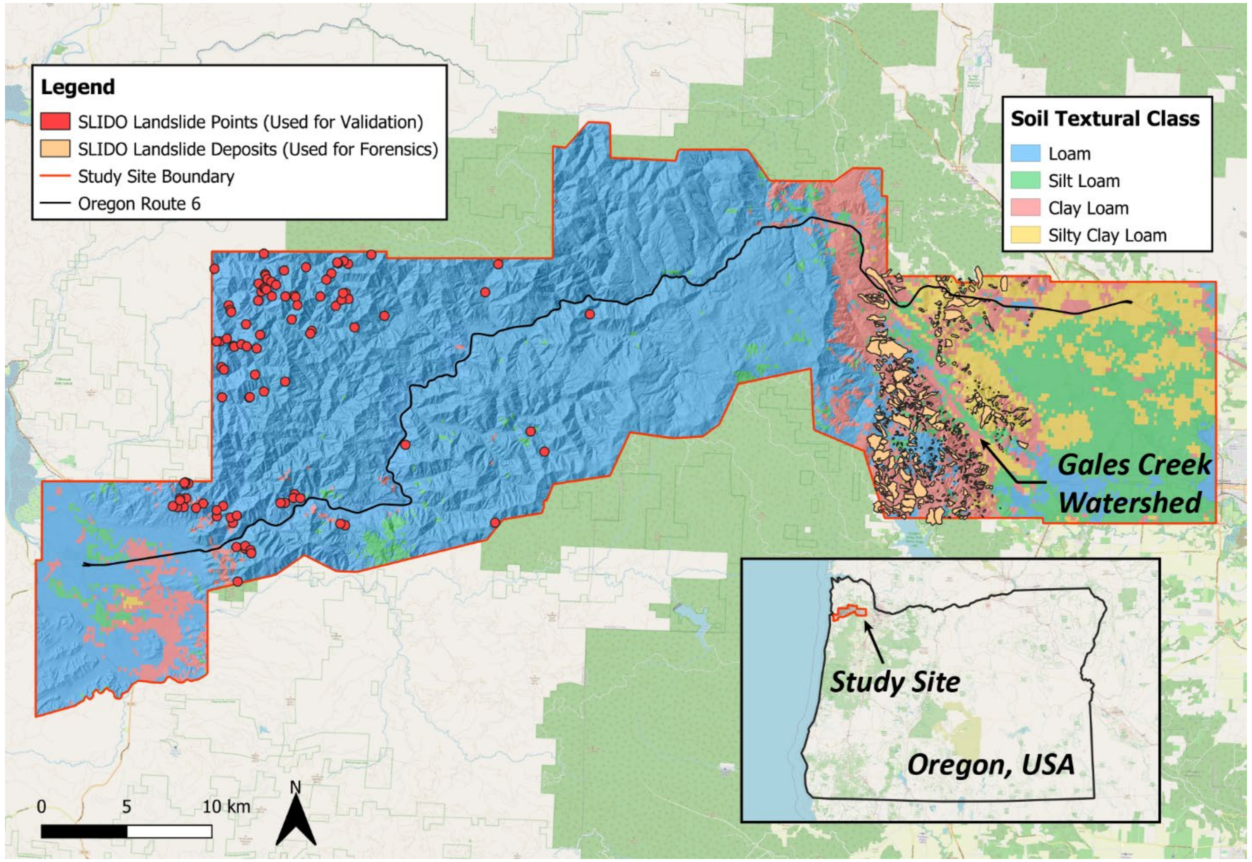

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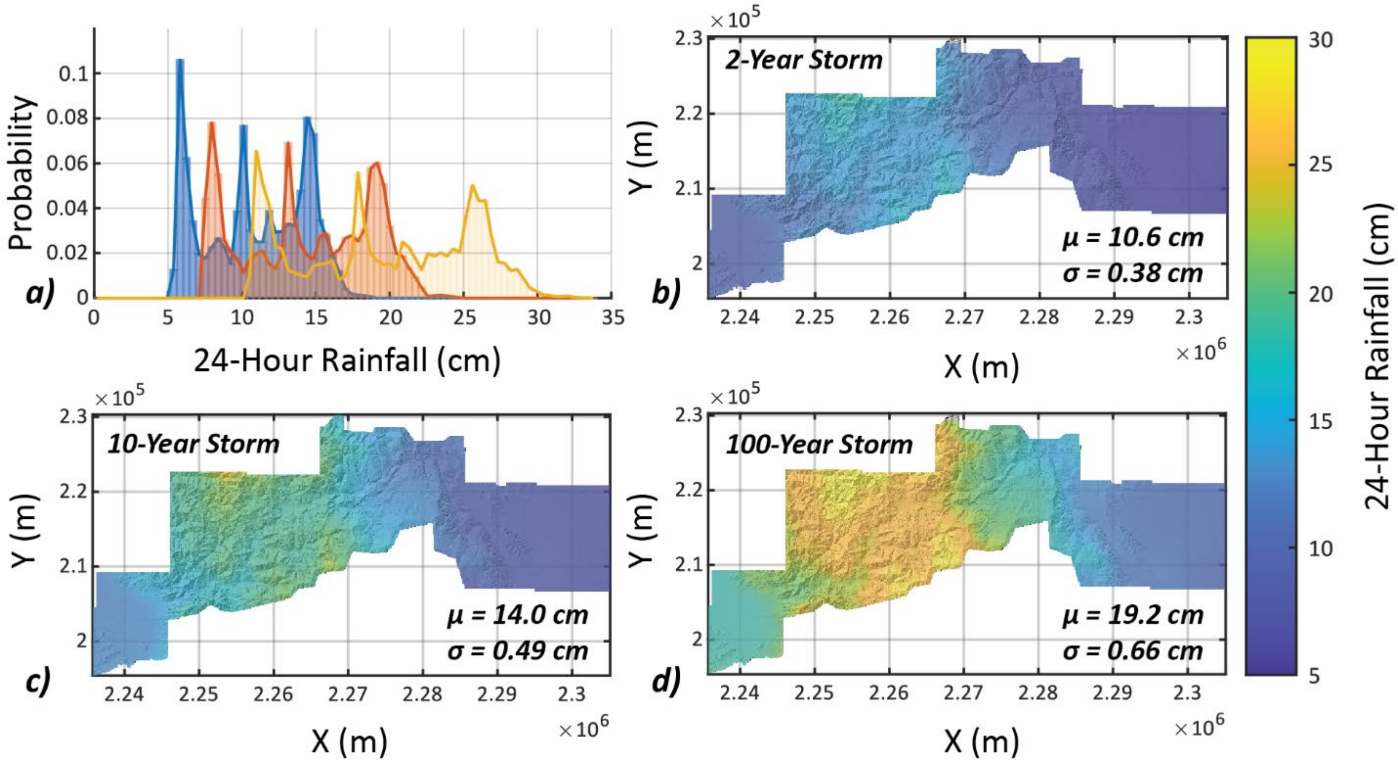

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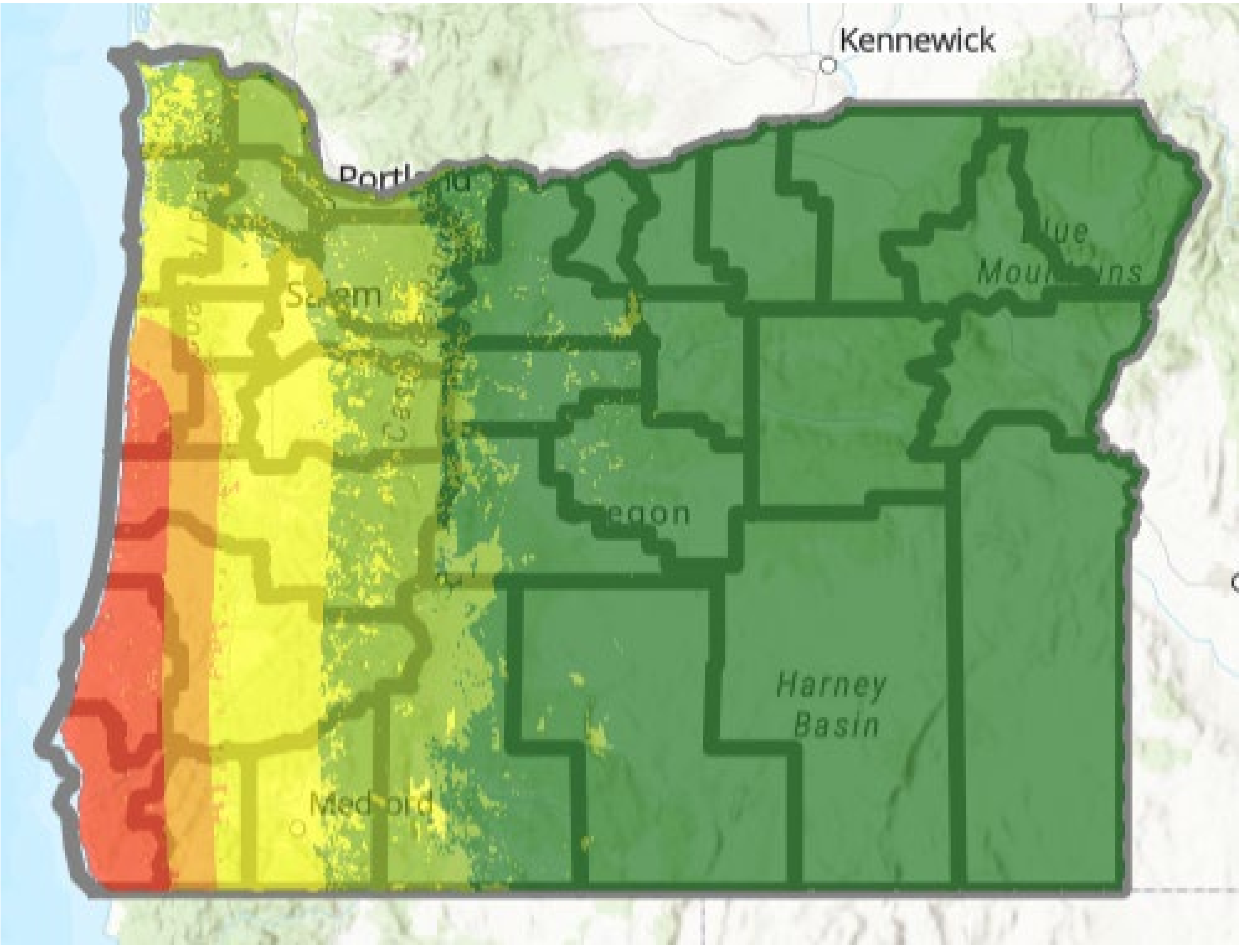
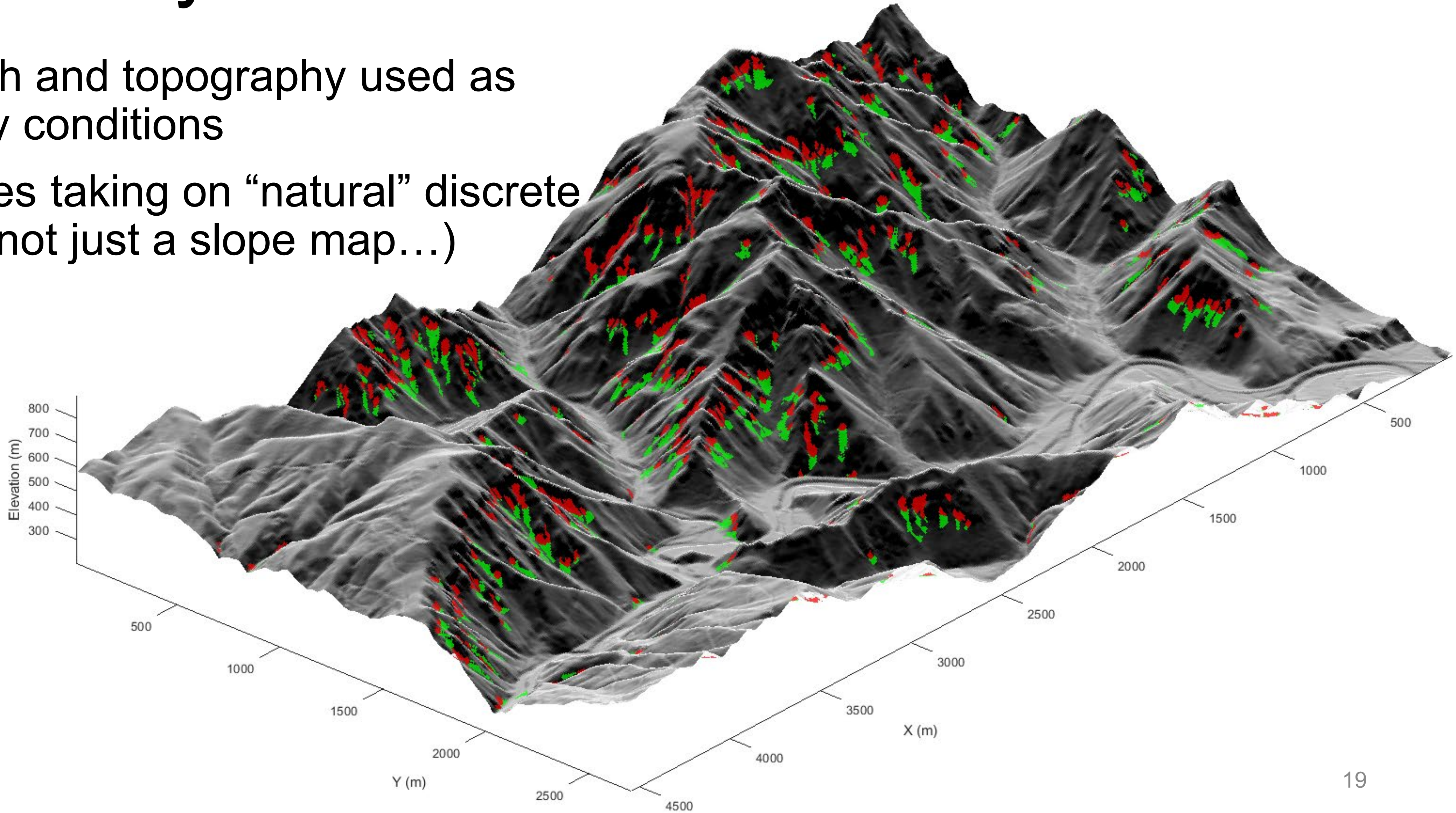


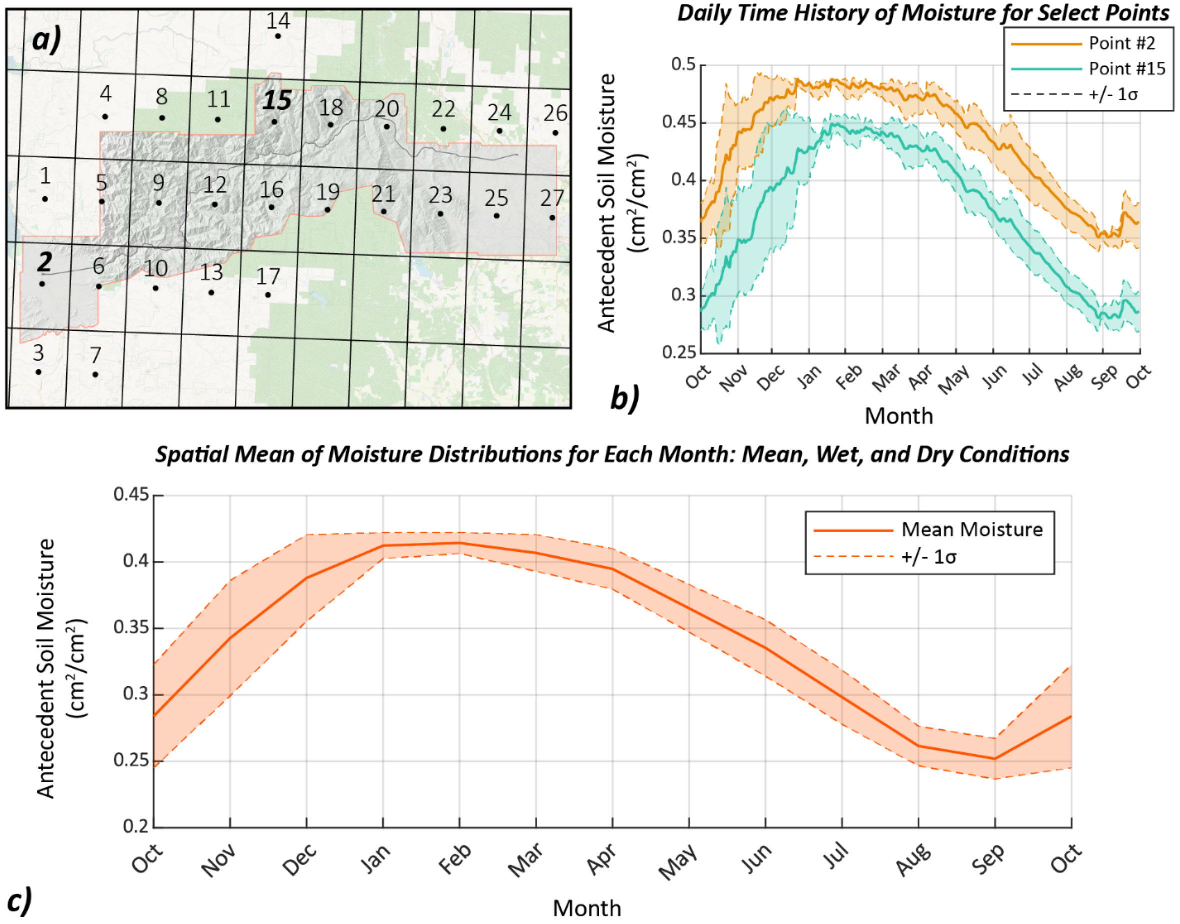
Susceptibility

- Soil depth and topography used as boundary conditions
- Landslides taking on "natural" discrete shapes (not just a slope map…)



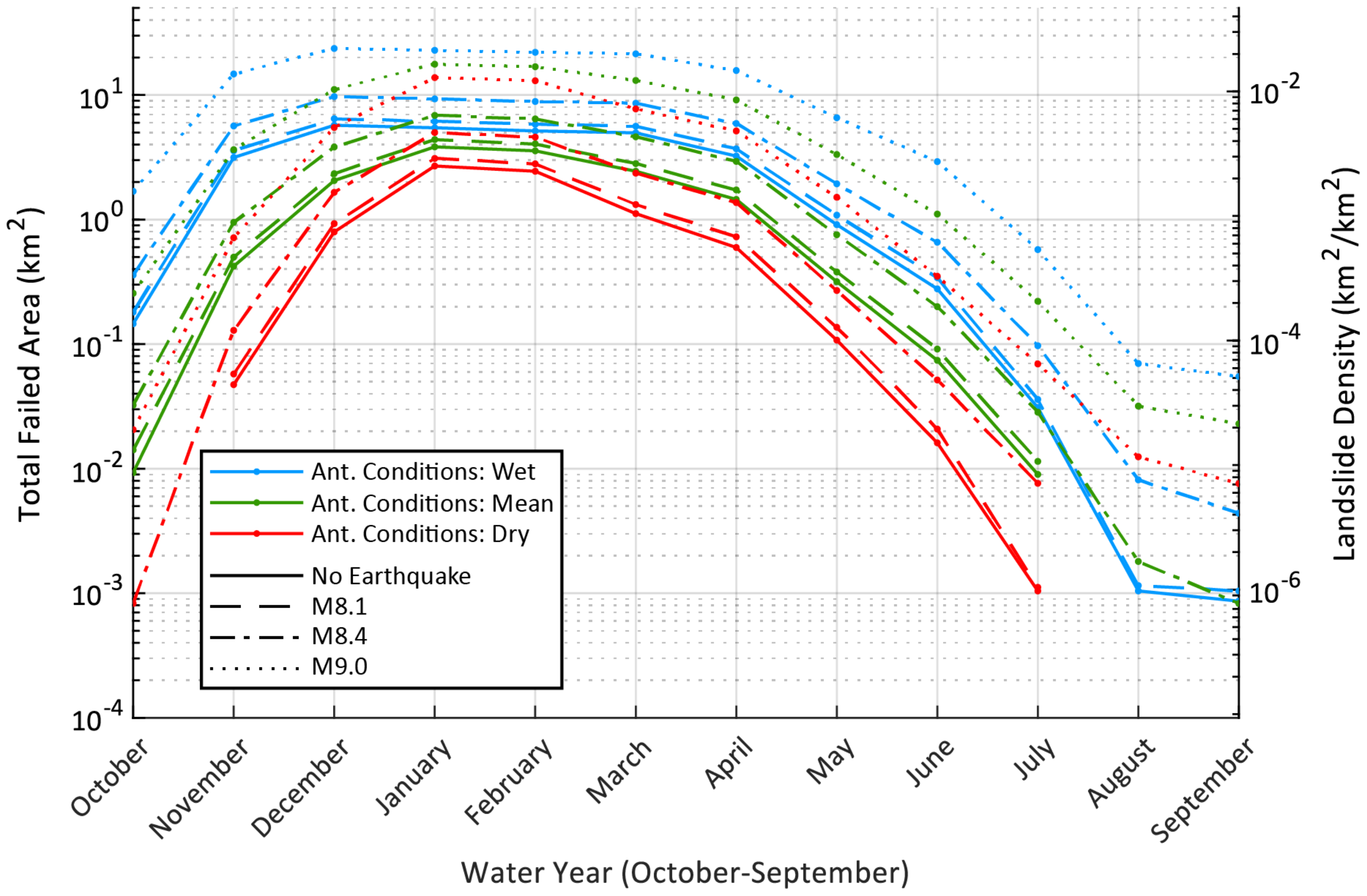
Role of Seasonality on Landsliding

- Have you ever wondered…how would coseismic landslide impacts be different in the wet versus dry months?
- How much does the overall "wetness" of the winter matter in terms of landslide triggering events?
- These questions revolve around evaluating *antecedent* moisture conditions.



Does it matter when the “big one” happens?

- Landslide area density changes with seasonal antecedent soil moisture.
- Seasonality shows up to 2-4 orders of magnitude more landsliding in winter vs. summer months.
- Wet conditions vs. dry results in 2-12 times more coseismic landslides.
- The bigger the earthquake, more landsliding.



Assessing Impact: Oregon Coast Range

- Lifelines serving Oregon coastal communities are at risk for severe landsliding events during future earthquakes.
- Performed landslide impact assessment of critical lifelines in the Oregon Coast Range
- Developed simple GIS tools to use overlapping landslide runout polygons + geometry to understand debris volumes.
- Used transportation + economic data to understand impact.

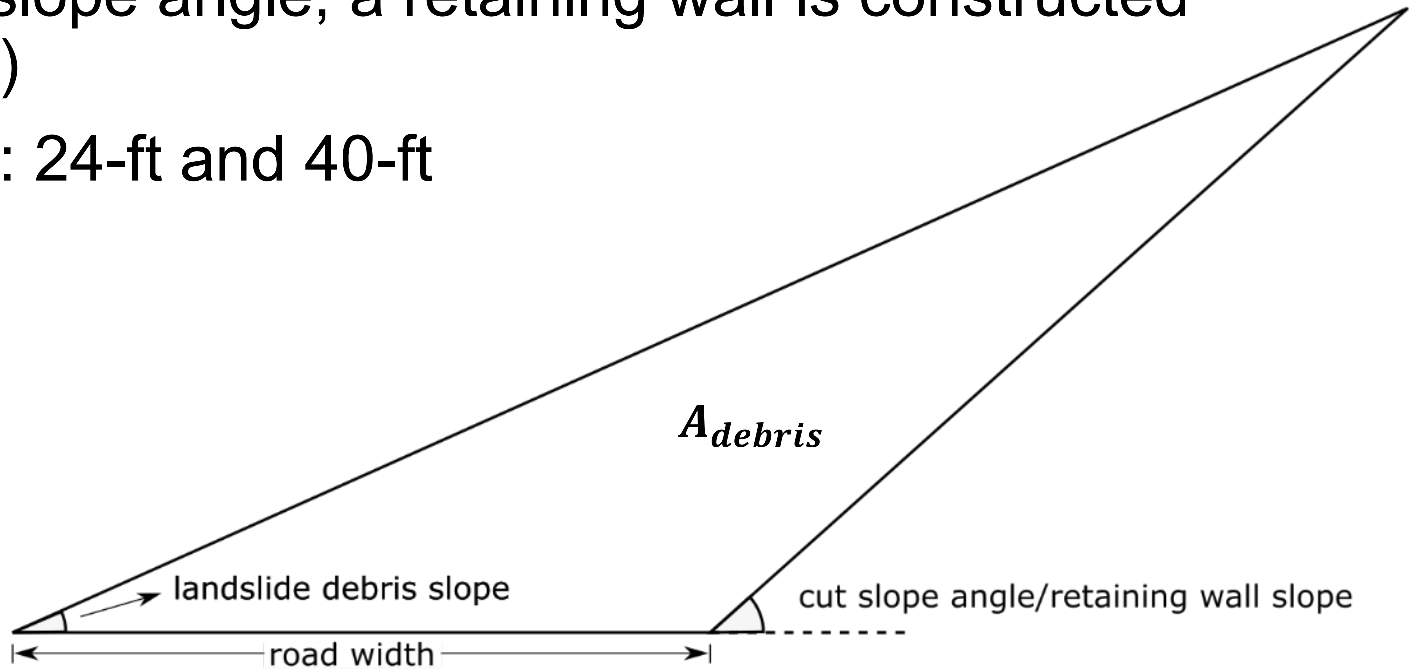
Impact Assessment: Closure and Expense

1. Use landslide clusters from susceptibility and associated runout to look at interaction with ODOT right-of-way (ROW)
2. Where landslides overlap ROW, time+cost of repair is assessed.
3. Result is time and cost of repair for each affected segment of highway and a total repair time and cost for entire corridor.

Repair Times and Costs – Debris Prism

- Create 3D prism of landslide debris on highway from lidar DEM
- Landslide debris slope = mean slope of superimposed landslide cluster
- Cut slope angle for emergency assumed to be 45°
- If landslide debris slope > cut slope angle, a retaining wall is constructed (small percentage of repairs…)
- Two highway widths assessed: 24-ft and 40-ft

$$V_{debris} = A_{debris} L_{hwy}$$



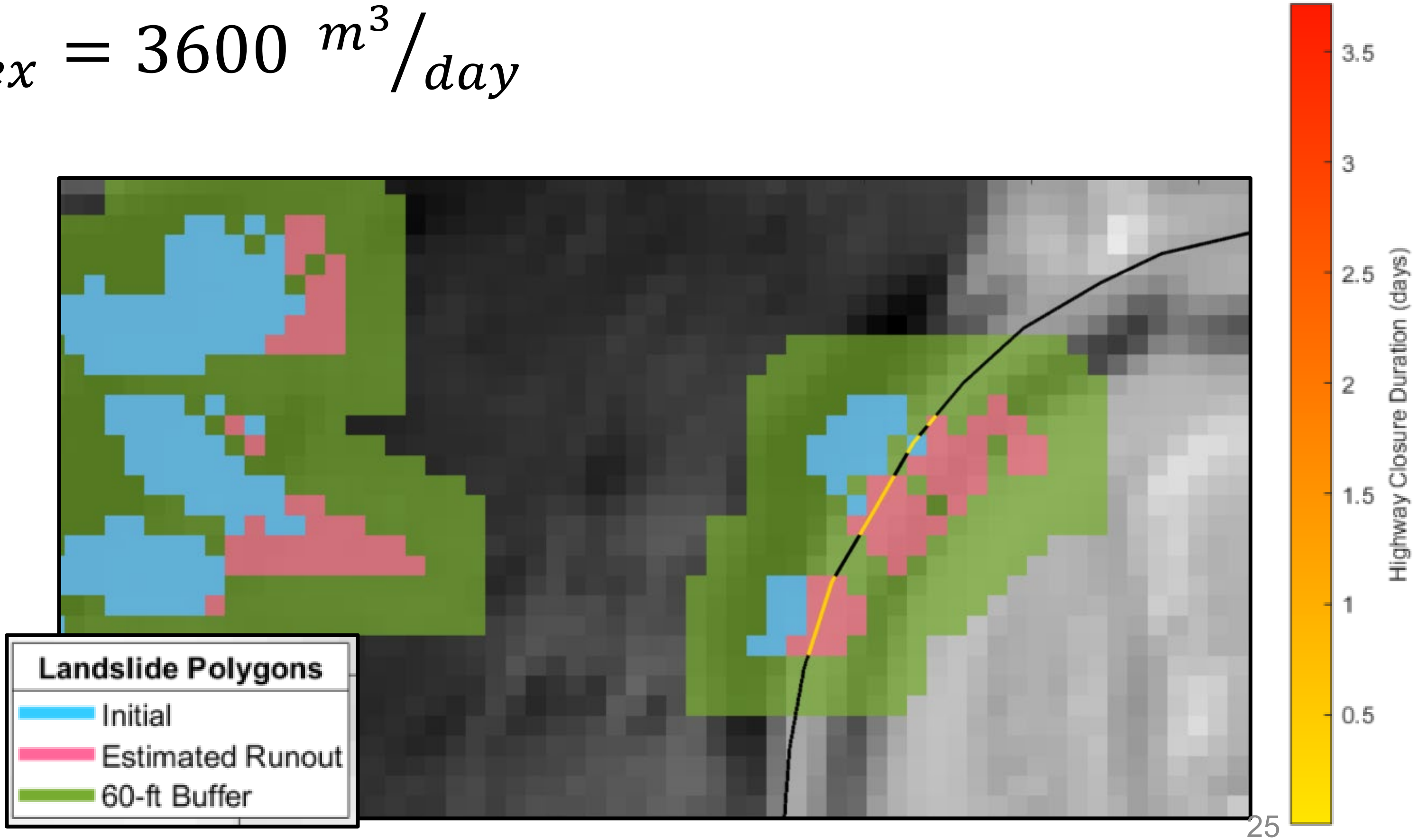
Repair Times and Costs – Duration of Closure

- Excavation rate:

$$R_{ex} = 5000\ {}^{yd^3}/_{day} \text{ -or- } R_{ex} = 3600\ {}^{m^3}/_{day}$$

- Duration of closure:

$$T_{closure} = \frac{V_{closure}}{R_{ex}}$$



Repair Times and Costs – Cost of Closure

- Repair costs from:
  - ODOT Unstable Slopes Database (for standard cut slope repairs)
  - 2018 ODOT Bridge Cost Data Sheet for 2016-2018 (for retaining wall repairs)

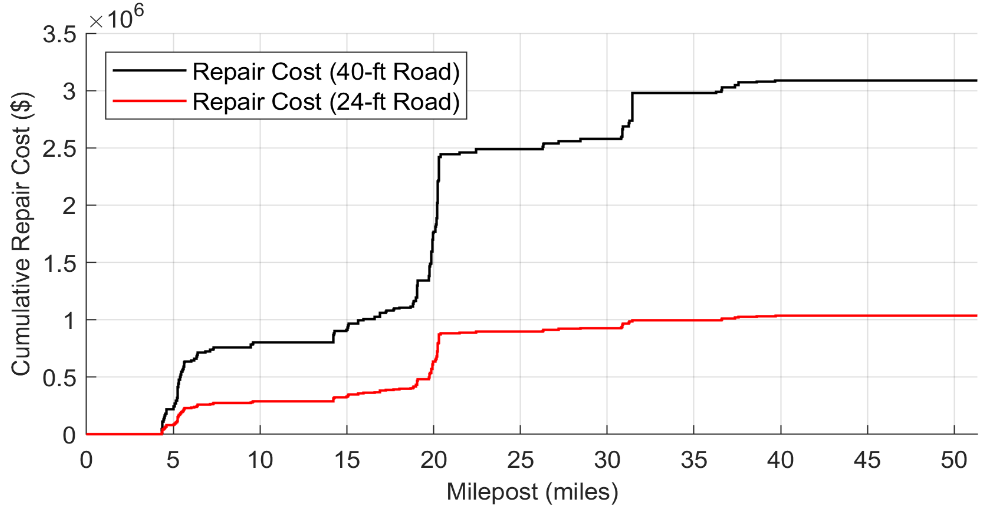
- For cut slope/retaining wall repairs, cost of excavation: $C_{ex} = \$14.40/m^3$

- For retaining wall repairs, wall construction cost: $C_{wall} = \$59.20/ft^2$

$$C_{repair} = \begin{cases} V_{debris}C_{ex}, & cut\ slope\ repair \\ V_{debris}C_{ex} + A_{wall}C_{wall}, & retaining\ wall\ repair \end{cases}$$

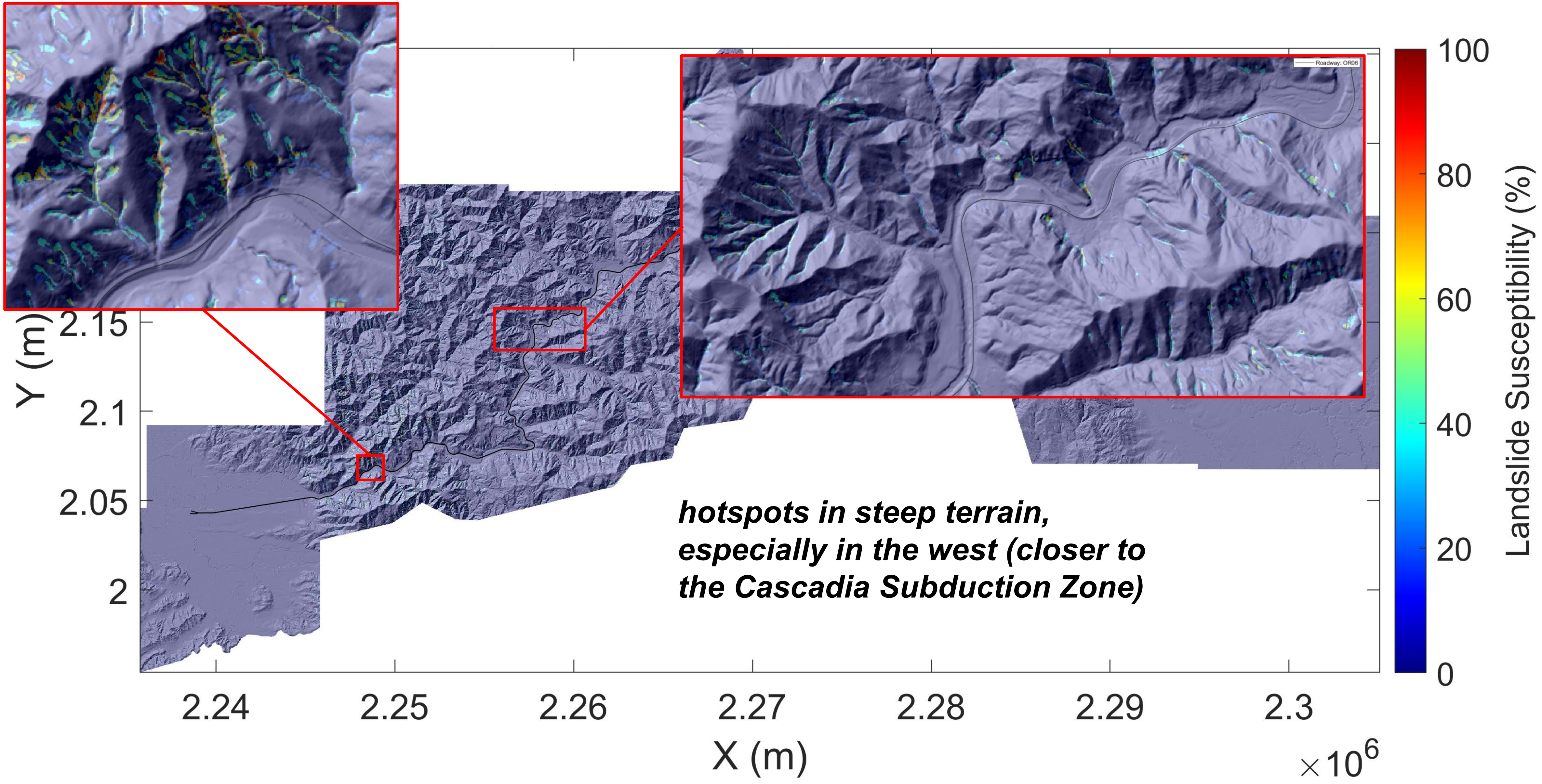
Repair Times and Costs – Cost of Closure

- Closure costs included in shapefile data for each corridor/scenario
  - May be easily mapped in GIS software by defining symbology by closure cost
- In report, costs are shown using profiles of milepost vs. cumulative repair cost:
  - Assuming both 24-ft and 40-ft width roadways
- Cost impacts generated using Transportation Planning and Analyses Unit (TPAU)

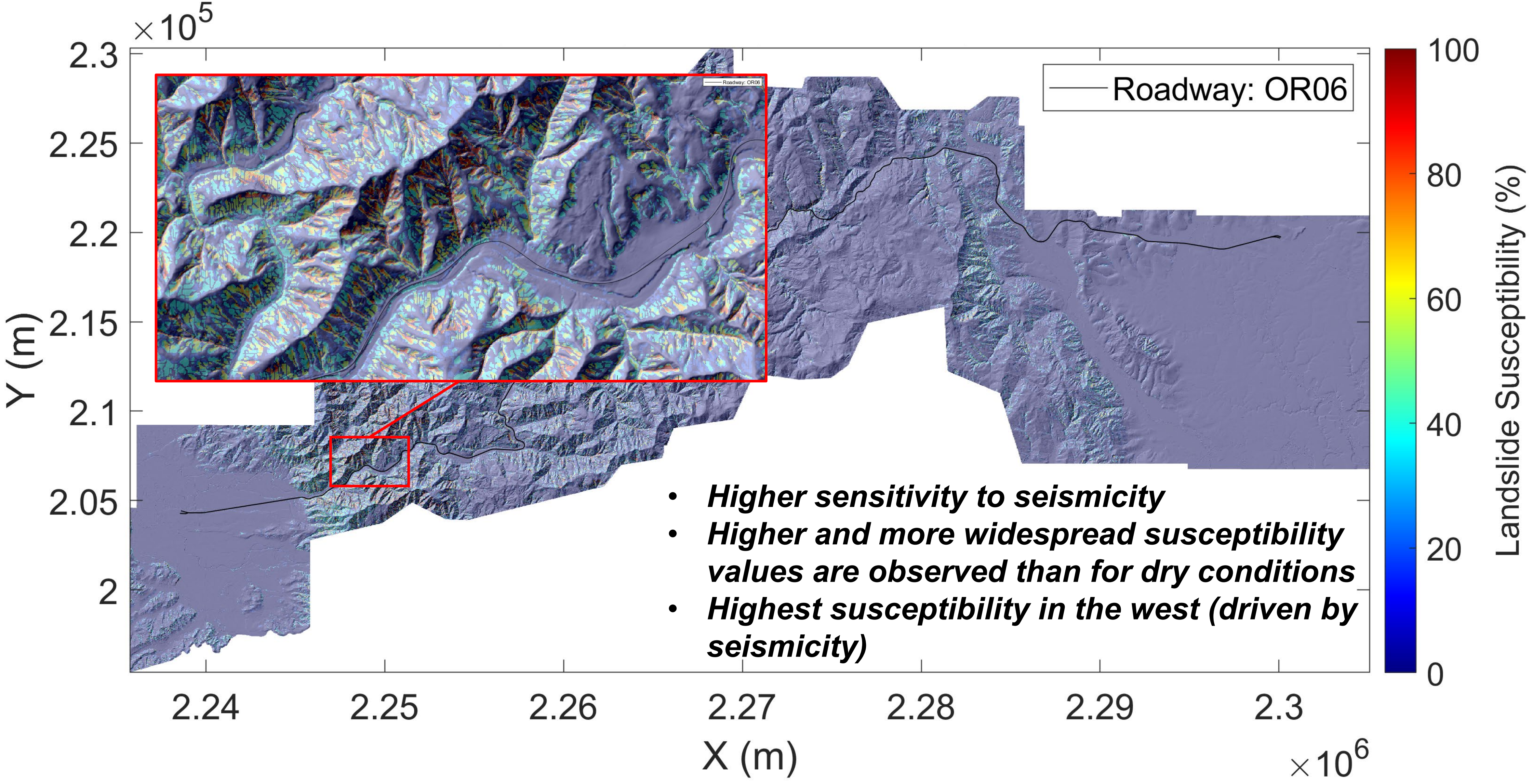


Daily Commodity Flow (USD)	
OR06	
Eastward	Westward
$410,389	$558,468
Average Daily Cost of Traffic Rerouting (USD)	
OR06	
$109,658	

August Antecedent Conditions – M8.7 Earthquake

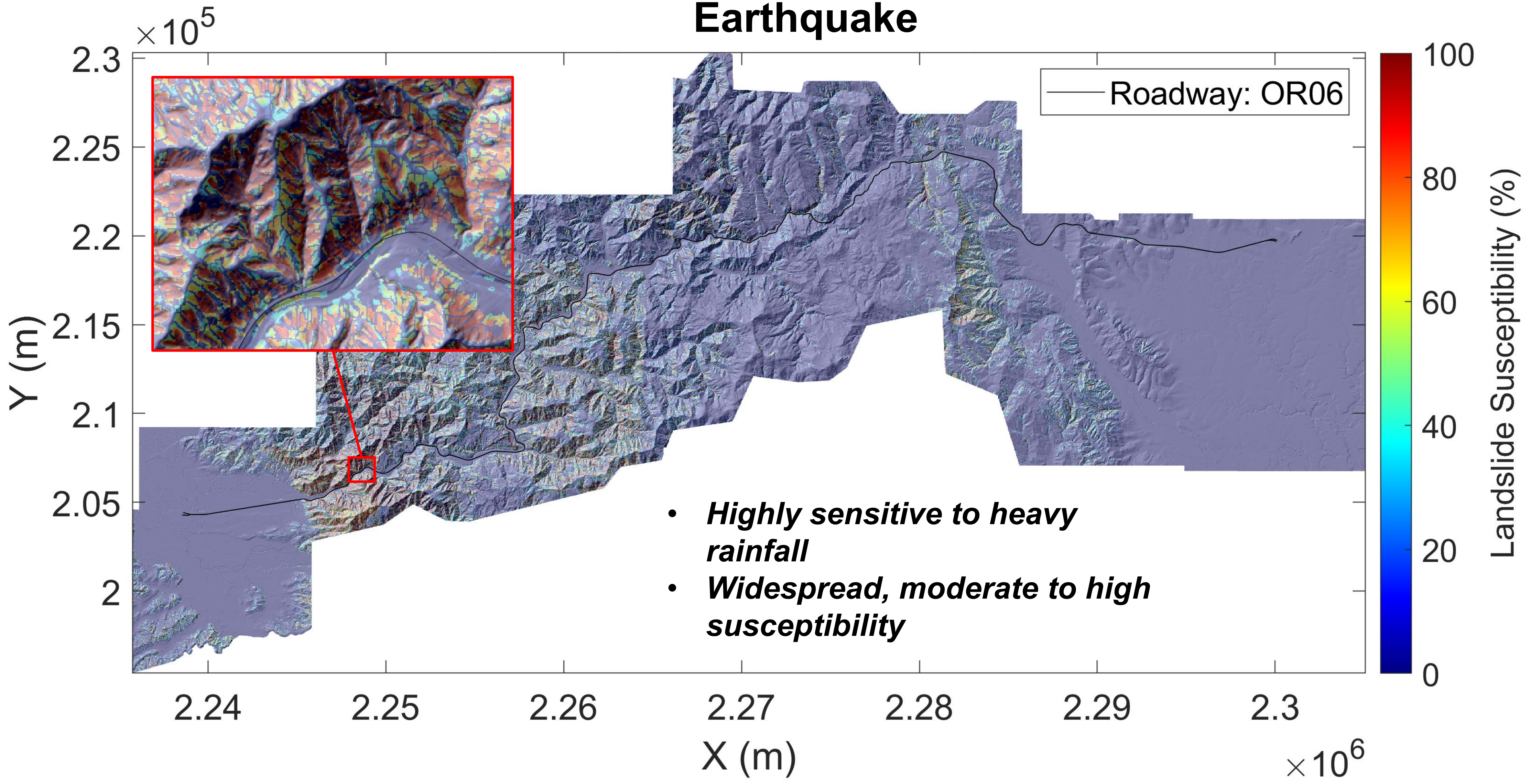


February Antecedent Conditions – M8.7 Earthquake



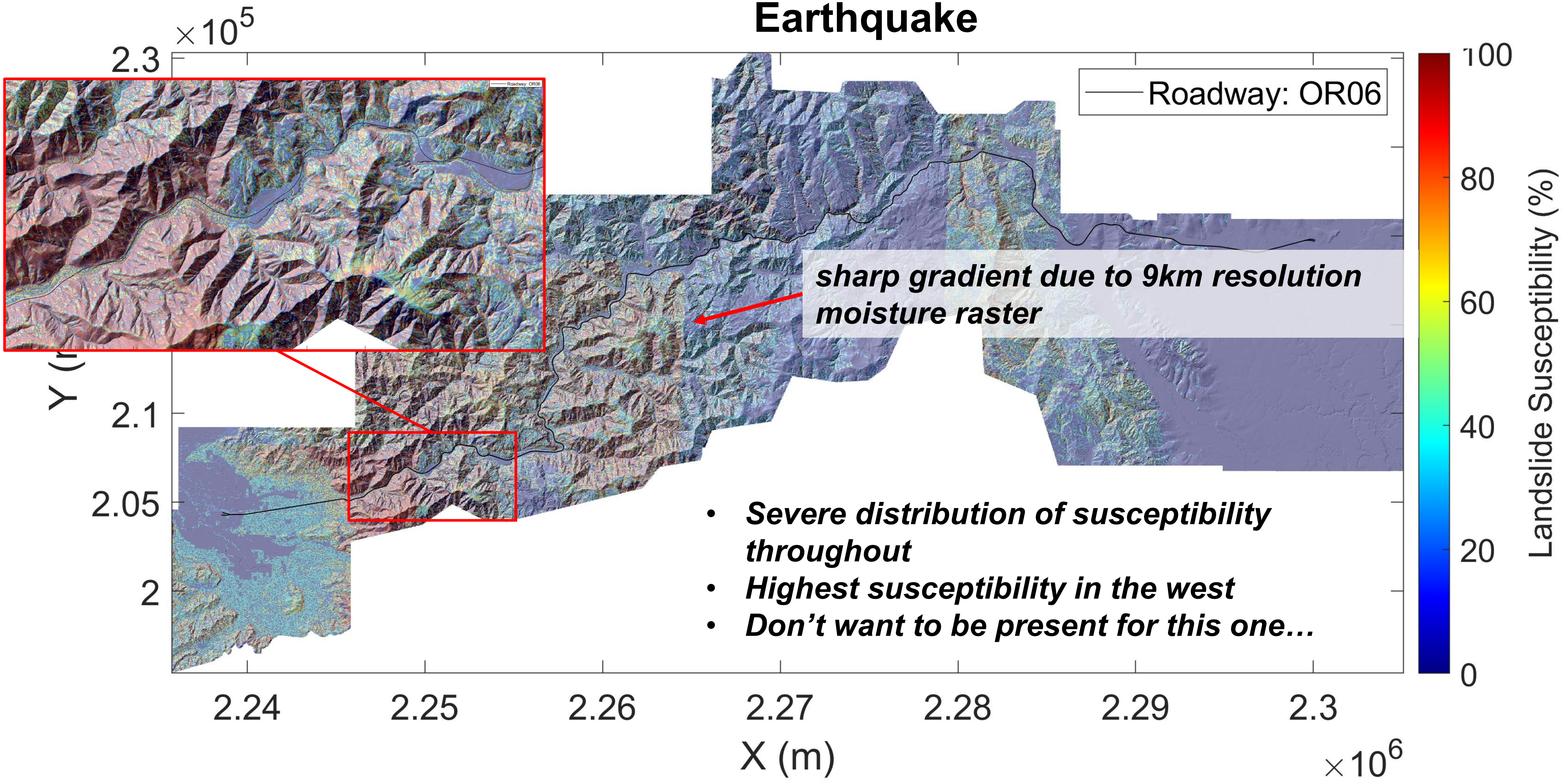
- ***Higher sensitivity to seismicity***
- ***Higher and more widespread susceptibility values are observed than for dry conditions***
- ***Highest susceptibility in the west (driven by seismicity)***

February Antecedent Conditions – 100-Year Storm - No Earthquake



- ***Highly sensitive to heavy rainfall***
- ***Widespread, moderate to high susceptibility***

February Antecedent Conditions – 100-Year Storm – M8.7 Earthquake



- ***Severe distribution of susceptibility throughout***
- ***Highest susceptibility in the west***
- ***Don't want to be present for this one…***

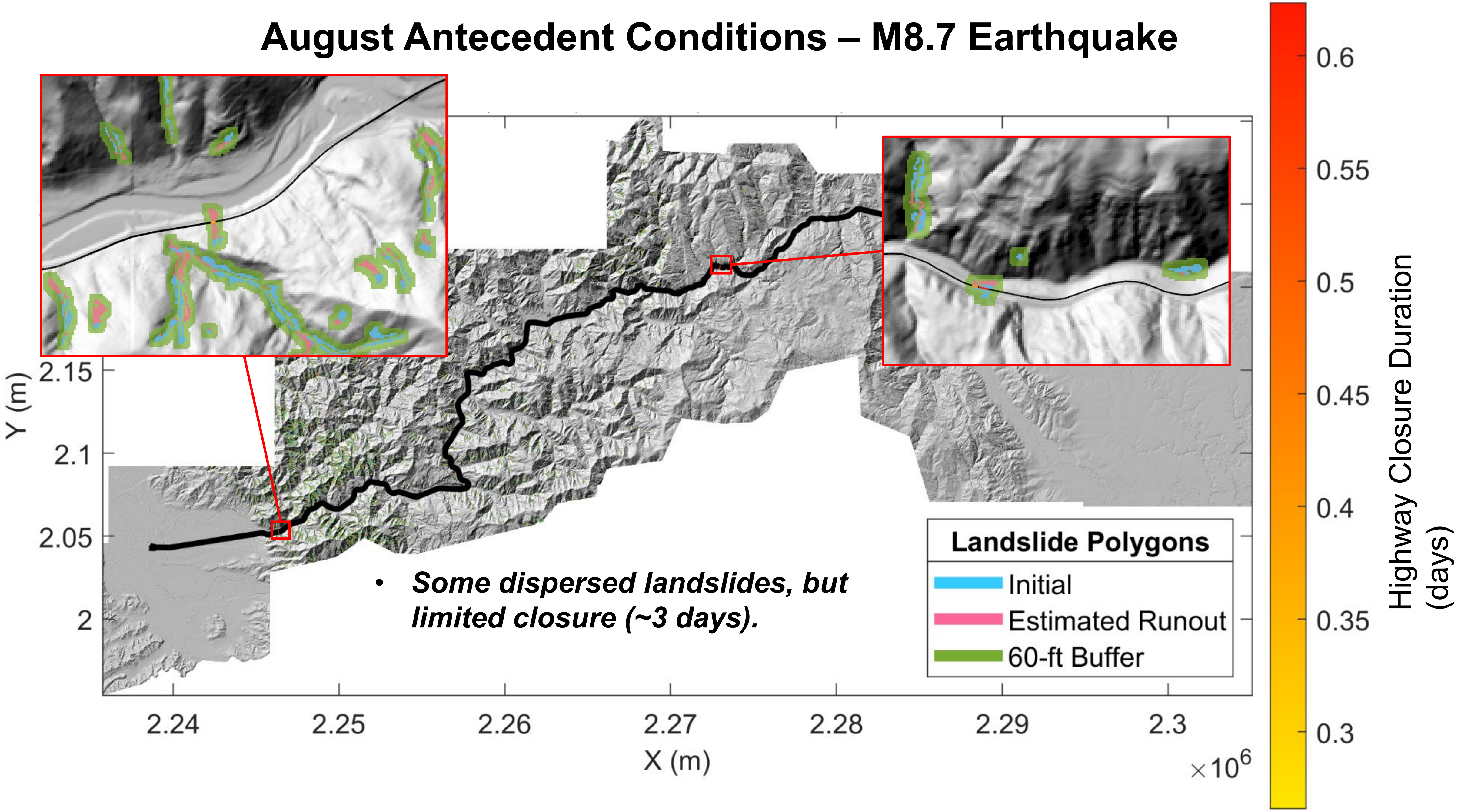
Susceptibility Observations

- Relatively stable in dry, summer conditions
- Susceptibility sensitive to moisture and rainfall, exacerbating susceptibility distribution during earthquakes
- Distribution of susceptibility varies depending on physical driver (e.g. rainstorm, seismicity, multi-hazard)

Risk Assessment

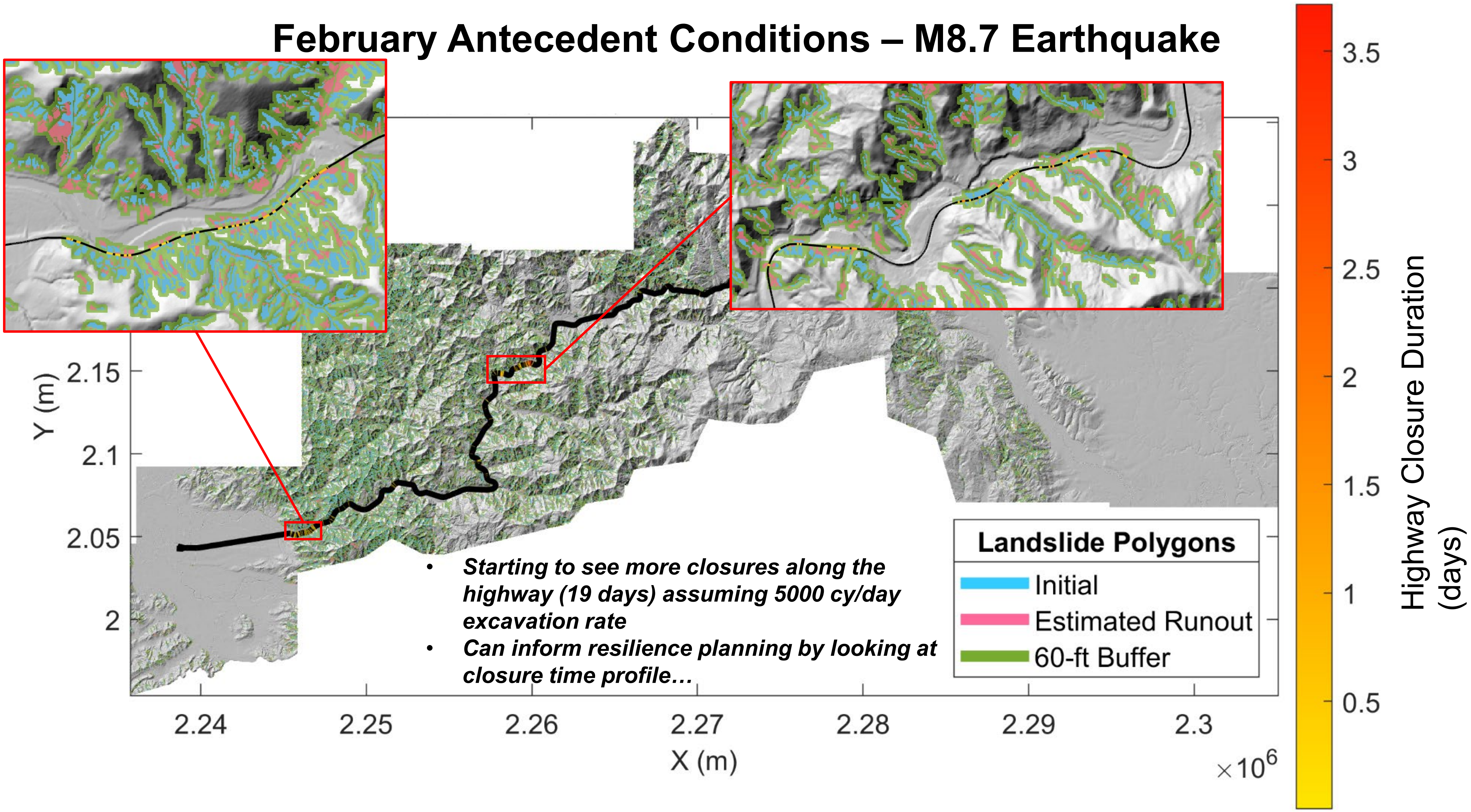
- Full suite of closure time maps, closure time profiles, and closure cost profiles available in SPR808 report
- Comprehensive table containing total closure times and costs, as well as event probabilities, commodity flow losses, and traffic rerouting costs available
- Shapefiles containing closure times and costs (all road widths and with/without 60-foot buffer)

August Antecedent Conditions – M8.7 Earthquake



- ***Some dispersed landslides, but limited closure (~3 days).***

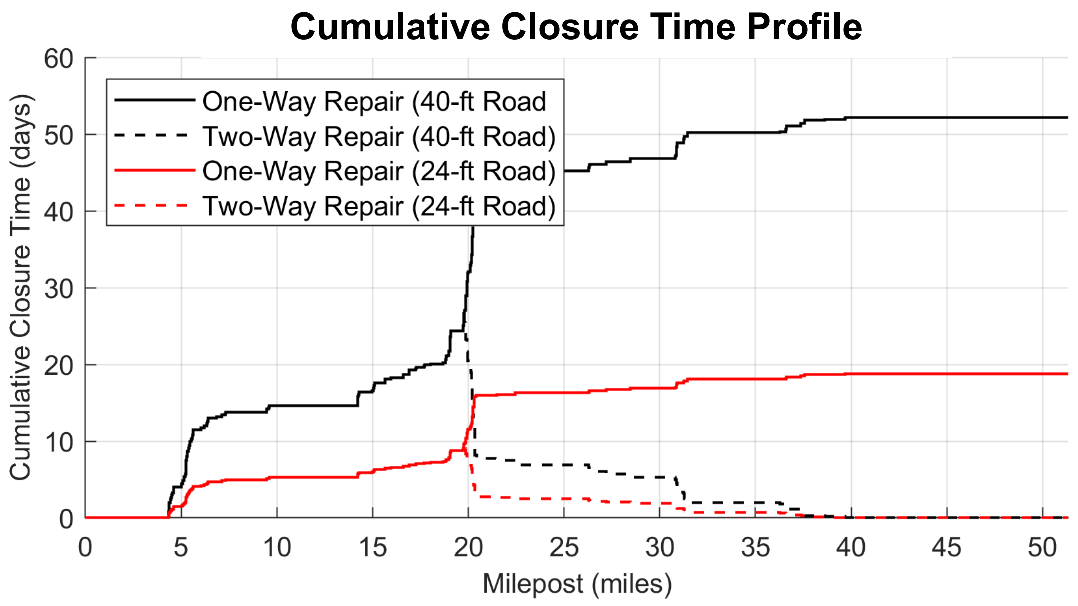
February Antecedent Conditions – M8.7 Earthquake

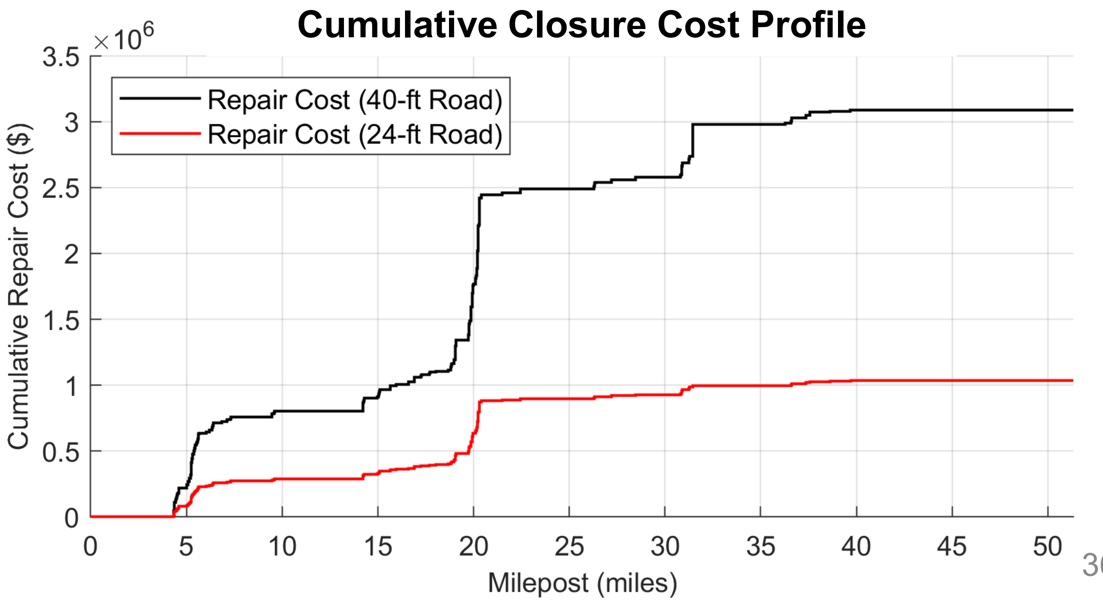


- ***Starting to see more closures along the highway (19 days) assuming 5000 cy/day excavation rate***
- ***Can inform resilience planning by looking at closure time profile…***

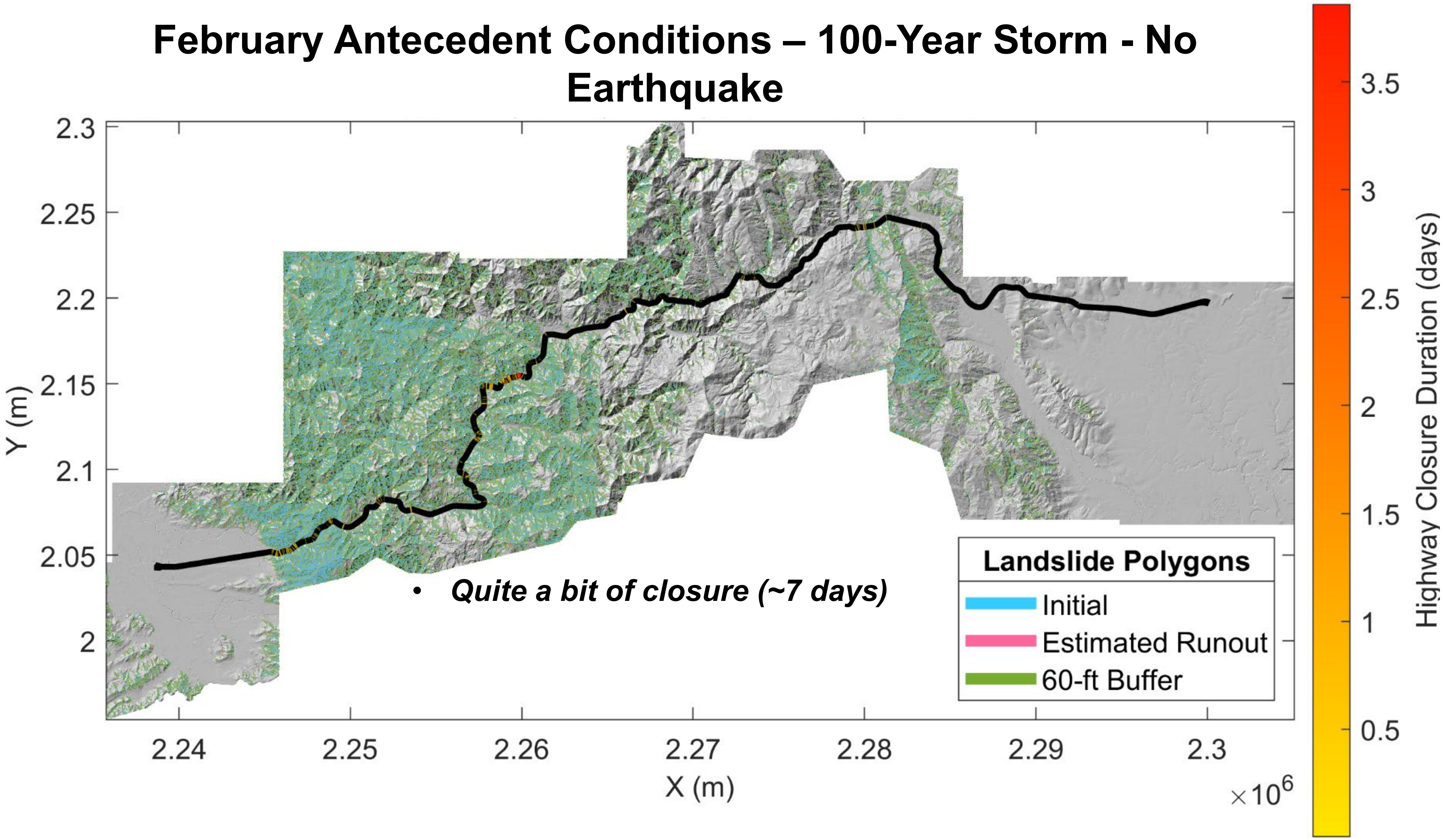
February Antecedent Conditions – M8.7 Earthquake

- Closed for:
  - 18.8 days (24-ft wide road)
  - 52.2 days (40-ft wide road)
- If repaired from both ends, time can ideally be reduced by half (dashed profiles)
- Cumulative cost shown as function of milepost



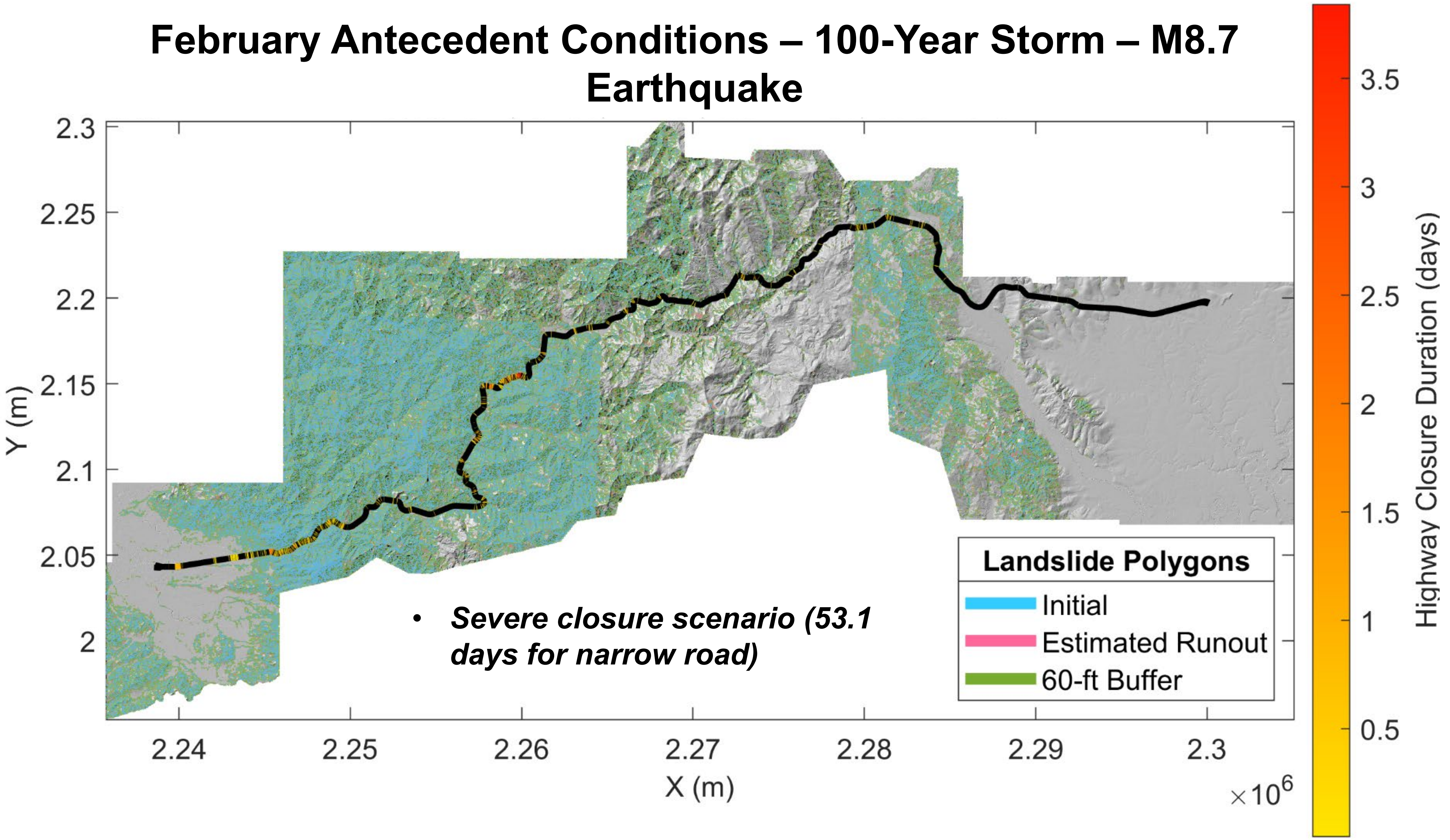


February Antecedent Conditions – 100-Year Storm - No Earthquake



- ***Quite a bit of closure (~7 days)***

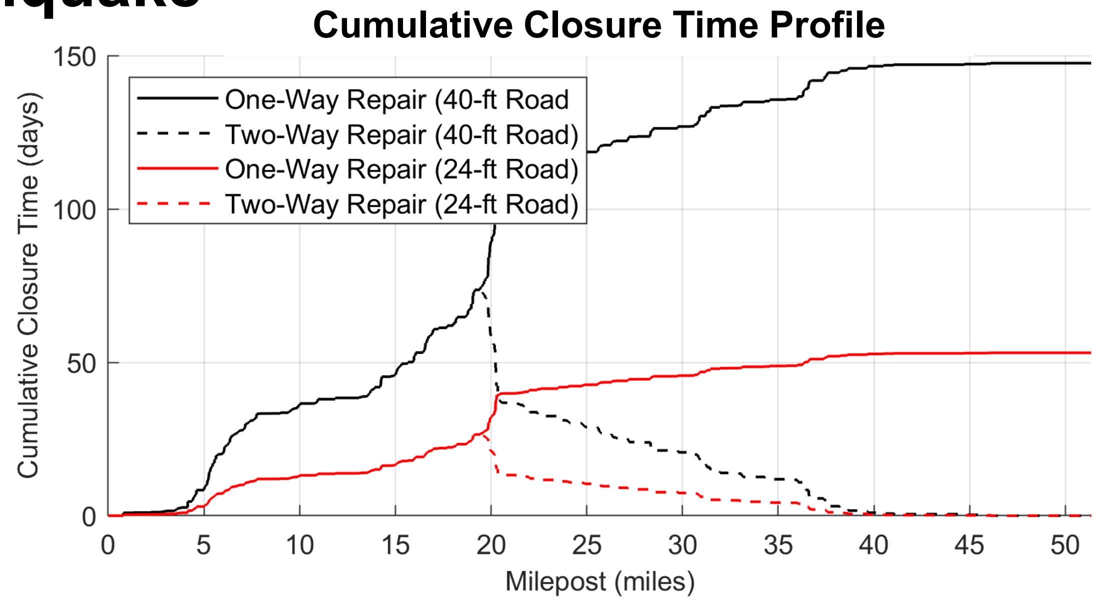
February Antecedent Conditions – 100-Year Storm – M8.7 Earthquake

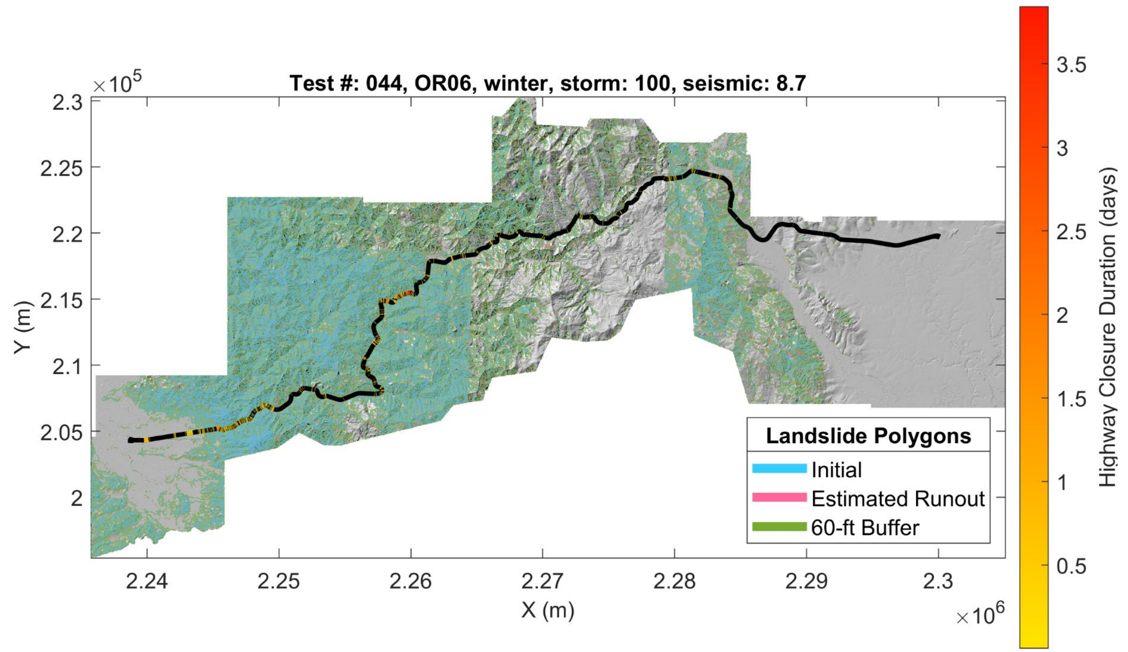


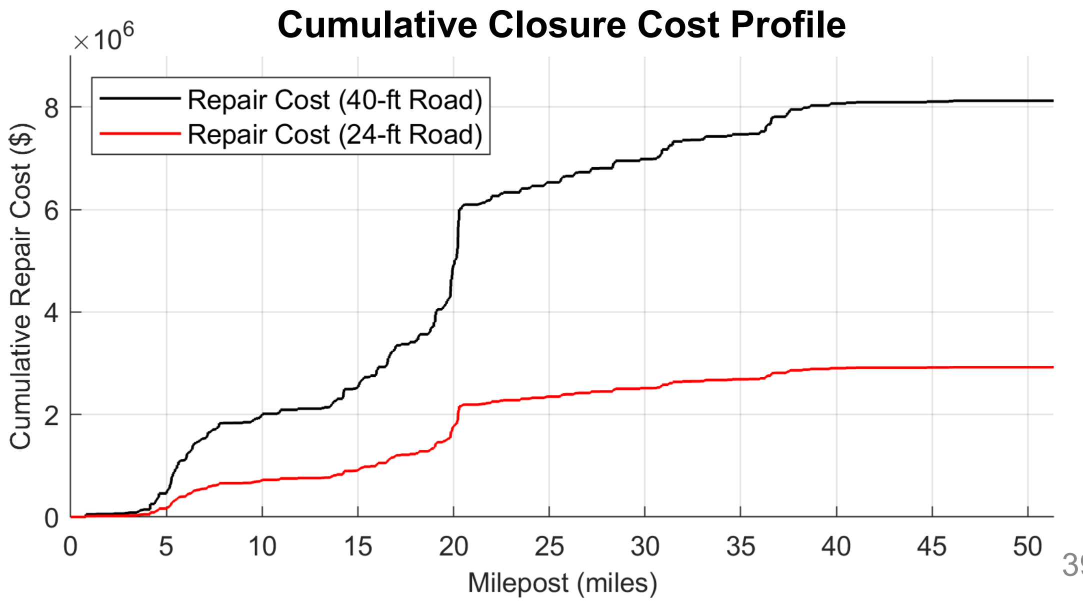
- ***Severe closure scenario (53.1 days for narrow road)***

February Antecedent Conditions – 100-Year Storm – M8.7 Earthquake

- Closed for:
  - 53.1 days (24-ft wide road)
  - 147.5 days (40-ft wide road)







Scenario-Based ROW Impacts

Test Information					Closure and Costs (40 ft Road Width)				Closure and Costs (24 ft Road Width)			
Test #	***Highway***	***Season***	***Rainfall***	***EQ Moment Magnitude***	***Closure Duration (days)***	***Total Repair Cost ($)***	***Commodity Loss ($)***	***Rerouting Loss ($)***	***Closure Duration (days)***	***Total Repair Cost ($)***	***Commodity Loss ($)***	***Rerouting Loss ($)***
1	US30	summer	off	off	7.47	$411,091	$17,105,522	$1,669,133	2.69	$211,745	$6,157,988	$600,888
4	US30	summer	off	8.7	33.03	$1,818,072	$75,650,136	$7,381,835	11.89	$722,501	$27,234,046	$2,657,460
6	US30	winter	off	off	125.22	$6,968,623	$286,832,704	$27,988,736	45.08	$2,763,962	$103,259,768	$10,075,943
9	US30	winter	off	8.7	131.93	$7,528,488	$302,182,880	$29,486,582	47.49	$3,017,910	$108,785,832	$10,615,168
16	US30	winter	100-year	off	122.65	$7,261,696	$280,935,552	$27,413,298	44.15	$2,855,909	$101,136,792	$9,868,785
19	US30	winter	100-year	8.7	172.72	$9,947,466	$395,614,336	$38,603,492	62.18	$3,946,541	$142,421,152	$13,897,256
26	OR06	summer	off	off	0.76	$41,637	$732,822	$82,943	0.27	$14,989	$263,816	$29,860
29	OR06	summer	off	8.7	1.65	$90,703	$1,596,401	$180,686	0.59	$32,653	$574,704	$65,047
31	OR06	winter	off	off	6.48	$356,719	$6,278,347	$710,603	2.33	$128,419	$2,260,205	$255,817
34	OR06	winter	off	8.7	52.17	$3,089,513	$50,546,760	$5,721,043	18.78	$1,312,383	$18,196,832	$2,059,576
41	OR06	winter	100-year	off	83.77	$4,737,137	$81,165,760	$9,186,600	30.16	$1,840,754	$29,219,676	$3,307,176
44	OR06	winter	100-year	8.7	147.53	$8,121,059	$142,932,512	$16,177,555	53.11	$2,923,581	$51,455,704	$5,823,921
51	US20	summer	off	off	0.00	$0	$0	$0	0.00	$0	$0	$0
54	US20	summer	off	8.7	0.00	$0	$0	$0	0.00	$0	$0	$0
56	US20	winter	off	off	6.47	$355,918	$8,953,142	$1,208,077	2.33	$128,130	$3,223,131	$434,908
						$3,334,091	$83,869,328	$11,316,76	21.80	$1,200,273	$30,192,956	$4,074,035

Climate Change Impacts on Shallow Landslides

- Climate change will result in wetter, warmer winters, more extreme rain events
- Current climatic conditions compared to future climate projection: RCP 8.5 (2040-2069)

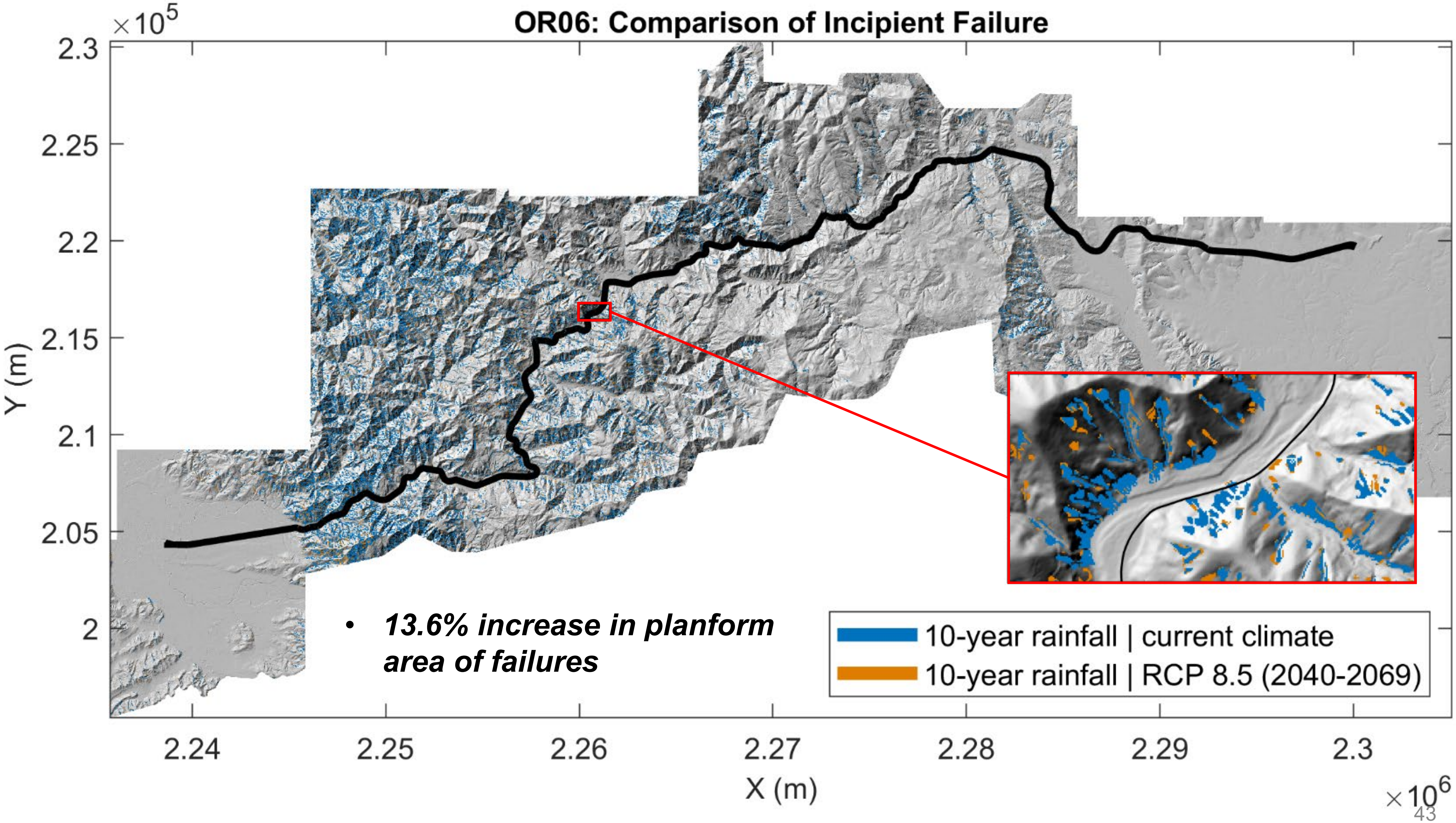
- Impact on landsliding quantified as:

1. Difference in number of failed cells
2. Percent change in susceptibility for each DEM raster cell

Again, we will focus on corridor OR06, but a full suite of results are available in the report and in SPR808 report.

Climate Change – Comparison of Incipient Slope Failure

- For current antecedent February conditions, we consider following rainfall events are applied:
  - 10-year storm (current climatic conditions)
  - 10-year storm (scaled by RCP 8.5, 2040-2060 anomaly)
- 50% susceptibility threshold applied to resulting susceptibility maps
- Blue cells show failed cells (≥ 50% susceptibility) under current conditions
- Orange cells show additional failed cells (≥ 50% susceptibility) after rainfall is scaled by anomaly

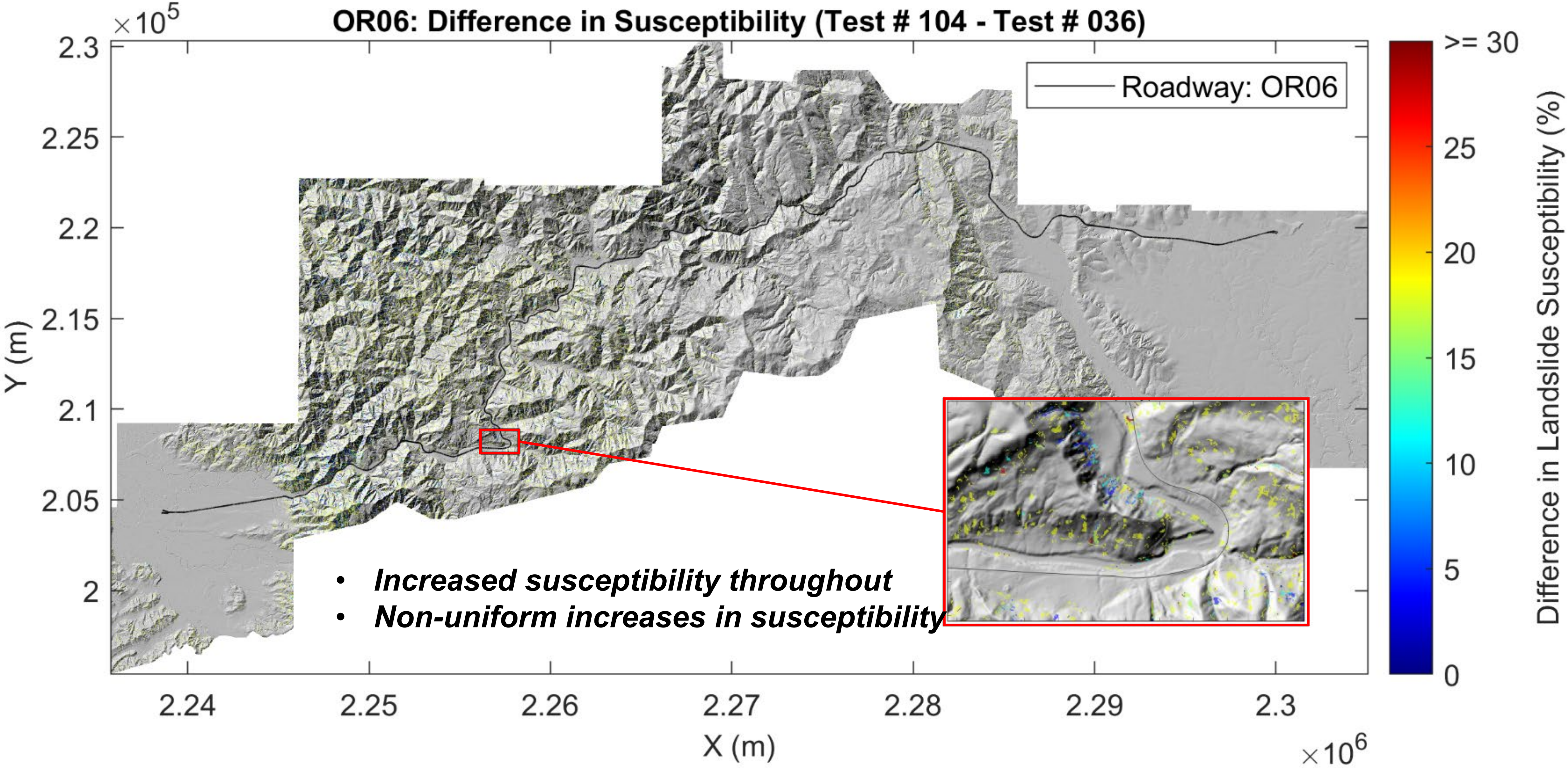


- ***13.6% increase in planform area of failures***

Climate Change – Percent Change of Shallow Landslide Susceptibility

- For current antecedent February conditions, the following rainfall events are applied:
  - 10-year storm (current climatic conditions)
  - 10-year storm (scaled by RCP 8.5, 2040-2060 anomaly)

- Visual comparison of raw distributions of landslide susceptibility



- ***Increased susceptibility throughout***
- ***Non-uniform increases in susceptibility***

Climate Change Assessment Summary

	Rainfall	Climatic Scenario	Failed Cell Area (km^2)[1]	% Increase in Failed Cell Area	Total Repair Cost[2,3]
US30					
	10-year	current	15.848	10.46%	$6,142,627
		RCP 8.5 (2040-2069)	17.505		$6,187,891
	10-year	current	56.380	13.63%	$3,026,188
		RCP 8.5 (2040-2069)	64.064		$3,234,754
US20					
	10-year	current	810.898	1.87%	$8,402,748
		RCP 8.5 (2040-2069)	826.080		$8,485,809
OR42					
	10-year	current	6.260	9.25%	$581,940
		RCP 8.5 (2040-2069)	6.839		$628,128

[1] Only incipient failure counted (landslide runout and buffer not included in count).
[2] Closure cost estimate includes estimated runout in analysis, but excludes landslide buffer.
[3] Closure cost analysis assumes 40-foot (12.2-m) wide roadway.

Climate Change Assessment Conclusions

- Increased rainfall, due to climate change, will increase:
  - The area of landslides in the assessed corridors
  - The distribution of landslides in the assessed corridors
- The increase in susceptibility is non-uniform due to:
  - Spatial variability in:
    - Soil types
    - Rainfall magnitude
    - Rainfall anomaly
    - Variations in local topography
- Repair costs of ODOT right-of-way may see an increase in repair costs and closure times for 10 year storms that are closer to “current” 100 year storm conditions.
- Increase of 2-14% in landsliding rates.

Conclusions: Applications of Susceptibility

- Susceptibility maps and TPAU outputs inform risk analyses, quantifying highway closure times and costs of highway repair, as well as commodity losses and costs tied to rerouting traffic during closure
- Corridors are shown to produce varying distributions of susceptibility depending on topography, antecedent moisture, rainfall events, seismic events, or multi-hazard events
- Susceptibility distributions driven by seismicity are shown to be exacerbated by high moisture and extreme storm events

Conclusions: Applications of Susceptibility

- Risk maps and risk profiles, showing the locations of closure “hot spots,” provide a glimpse of the potential impact of a large CSZ earthquake, suggesting that planners may:
    1. Place stockpiles of materials or equipment strategically to expedite post-disaster recovery
    2. Choose to implement mitigation techniques in areas that are unstable but of manageable size
    3. Make decisions regarding the scope of repairs in context of reopening and/or safety

Questions?

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    - ODOT-SPR-808
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