INFORMING PREDICTIONS FROM ABOVE WITH COMMUNITY DATA FROM BELOW: A MECHANICS-INFORMED AI LIQUEFACTION MODEL FOR RAPID RESPONSE & SIMULATION

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PEER Researcher's Workshop
16 August 2024

Outline

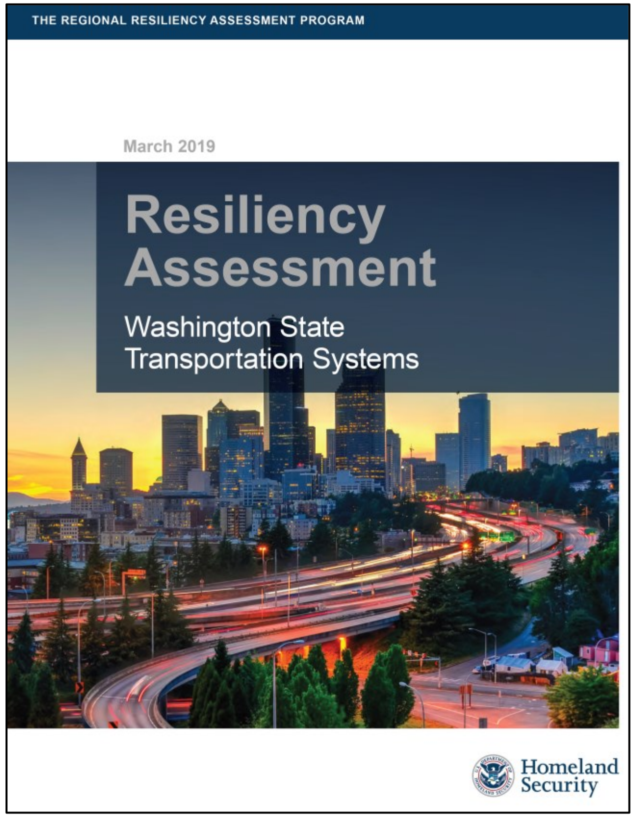
Motivation & Background — Goal — Model Concept/Demo — Benefits — Ongoing & Future Work

Motivation

➢ *Liquefaction routinely damages infrastructure, hinders post-event mobility and recovery.*

Motivation

- *Some scenario earthquake studies suggest liquefaction could cause more damage than any other earthquake effect:*



- *The Dept. of Homeland Security (2019) predicted impacts to infrastructure owed by WA state in an M9 earthquake.*

2755 km of road, 1815 km of rail, 837 bridges, and 8 ports are expected to be unavailable due predominantly to soil liquefaction.

- *<u>Draws attention to</u>:*

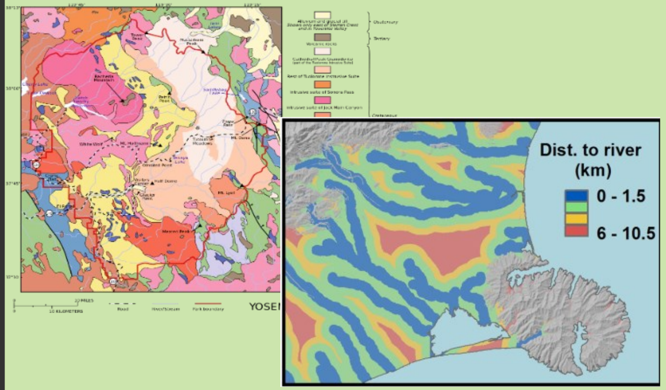
1) *Liquefaction's potentially staggering impact (could these predictions be true?!)*
2) *How liquefaction is predicted at regional scales (DHS used "HAZUS" type model)*

Background

➢ *Liquefaction models can be viewed as having 3 tiers:*

<u>Tier 1</u>

Geologic/Geospatial Models

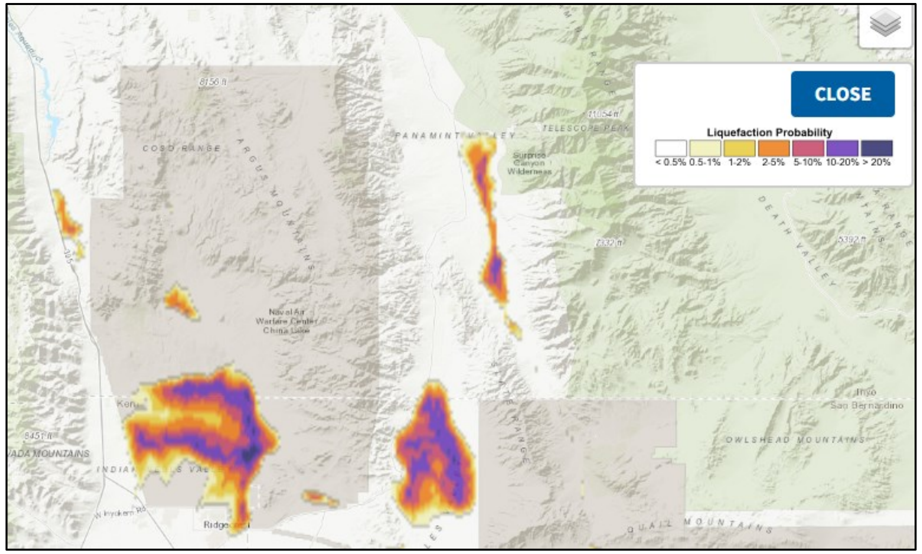


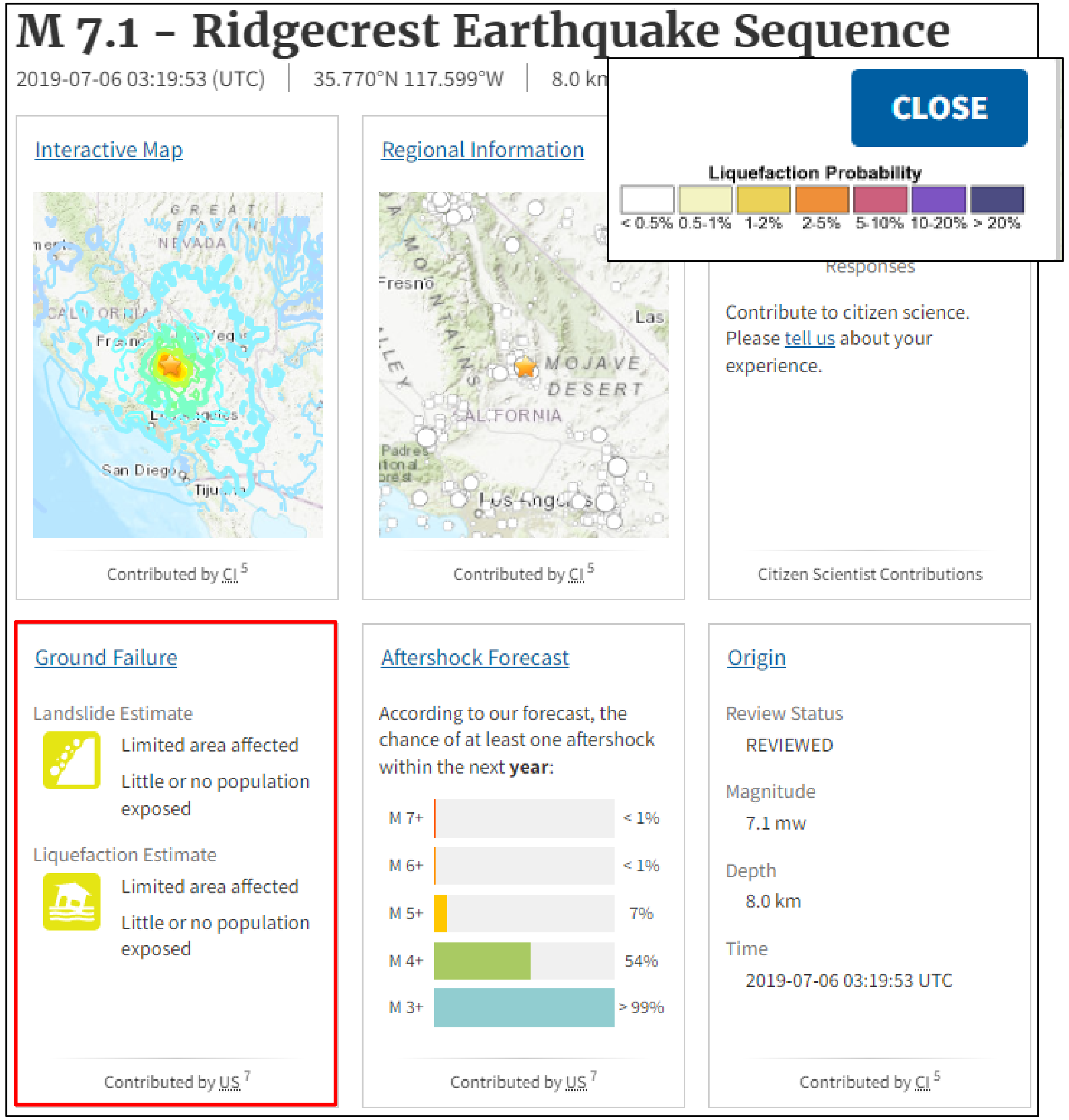
➢ ***<u>Tier 1</u>:*** *Requires only geologic or geospatial data. Used at regional scale. A range of complexities, but all are limited by lack of subsurface data (e.g., HAZUS).*

Background: Tier 1 Models

<u>*For example, Rashidian & Baise (2020):*</u>

- *Adopted by USGS for regional predictions in near-real-time and for future scenario events.*
- *Five variables: V_{S30}, precipitation, depth to water, distance to water, PGV.*
- *Trained on global liquefaction observations.*
- *Similar models used internationally.*





[1] *Rashidian, V., & Baise, L. G. (2020). Regional efficacy of a global geospatial liquefaction model. Engineering geology, 272, 105644.*

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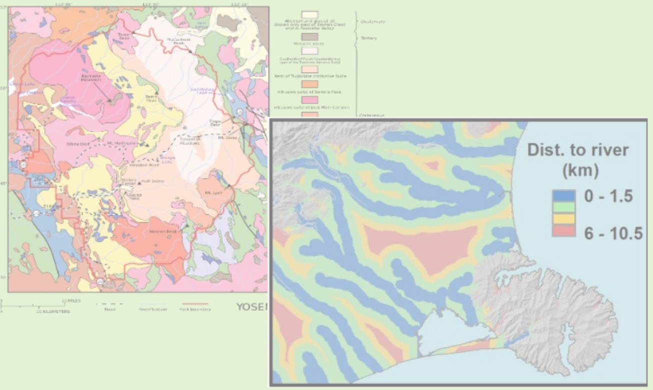
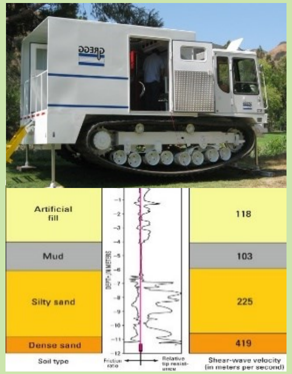
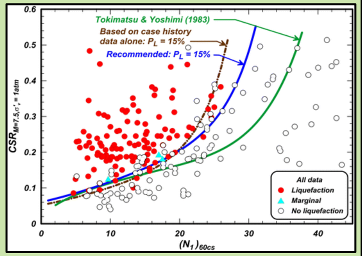


Tier 2

"Stress-Based" Models





➢ *<u>Tier 1</u>: Requires only geologic or geospatial data. Used at regional scale. A range of complexities, but all are limited by lack of subsurface data (e.g., HAZUS).*

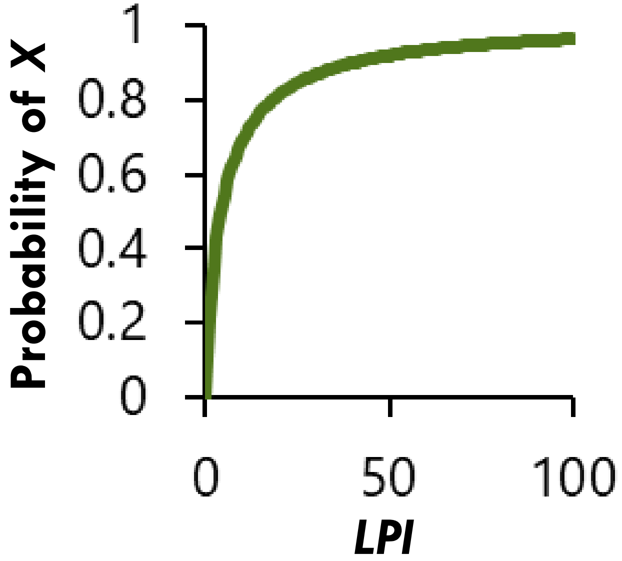
➢ ***<u>Tier 2</u>:** Requires in-situ geotechnical test data. Used at site scale. Most widely validated and commonly used model in engineering practice.*

Background: Tier 2 Models

- *Several types of in-situ data can be used, but Cone Penetration Test (CPT)-based models are generally favored (~$3k-$10k per test):*

Triggering/Incidence Models

Ground Deformation
Pipeline Damage
Foundation Damage
Building Damage Ratio ($)
Etc.



Manifestation/Consequence Models

Liquefaction Potential Index (*LPI*)
Ishihara Inspired *LPI* (LPI_{ISH})
Liquefaction Severity Number (*LSN*)
Ishihara Inspired *LSN* (LSN_{ISH})
NGL models and others forthcoming…

Prediction of profile/system response

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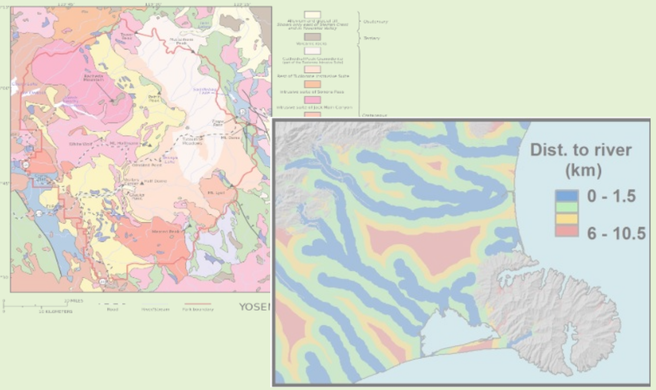
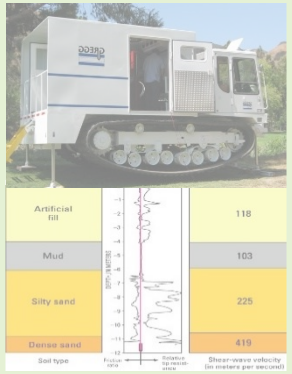
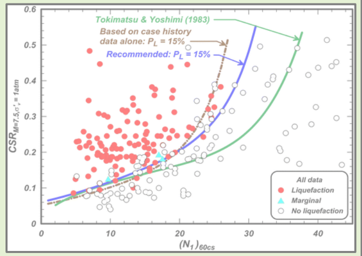


Tier 2

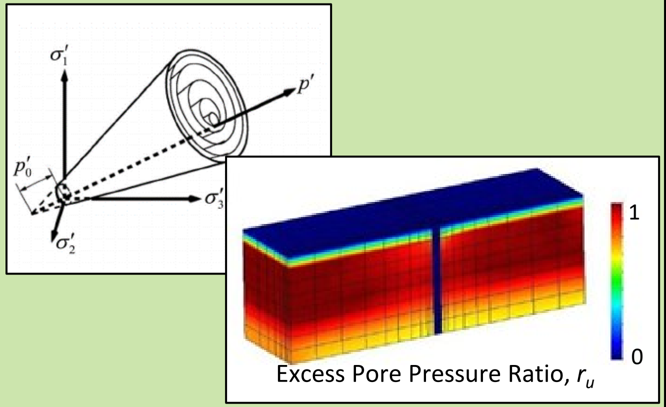
"Stress-Based" Models





Tier 3

Constitutive Models



➢ ***Tier 1**: Requires only geologic or geospatial data. Used at regional scale. A range of complexities, but all are limited by lack of subsurface data (e.g., HAZUS).*

➢ ***Tier 2**: Requires in-situ geotechnical test data. Used at site scale. Most widely validated and commonly used model in engineering practice.*

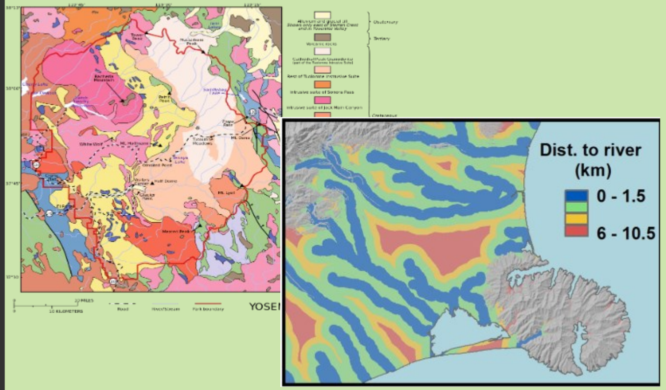
➢ ***Tier 3**: Requires many soil and model parameters. Used at project scale. Can provide additional spatial/temporal insights.*

Background

➢ *Liquefaction models can be viewed as having 3 tiers:*

Tier 1

Geologic/Geospatial Models



Tier 2

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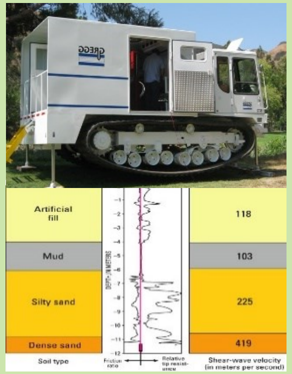

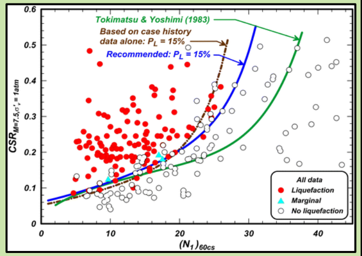

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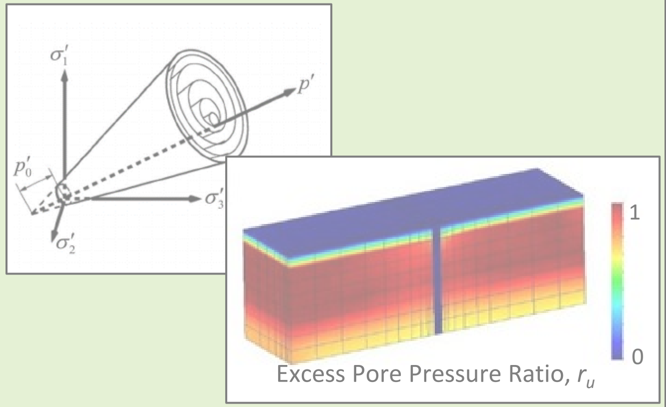

Our focus.

Tier-1 models have important uses but major limitations.

How can Tier-2 data and models be used to improve them?

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Project Goal

- ***Current Tier 1 models have some major limitations:***

1. *They do not exploit the available geospatial information.*
   (accurate inference of subsurface conditions surely requires more than 4 variables)

2. *They do not benefit from knowledge of liquefaction mechanics developed over 50+ yrs.*
   (models are trained only on observations, have no mechanistic backbone)

3. *They are not informed by, or anchored to, measurements of subsurface conditions.*
   (subsurface data is plentiful in many regions but is not used, often contradicts models)

- ***Goal:*** *Development of a Tier-1 model that addresses each of these limitations.*

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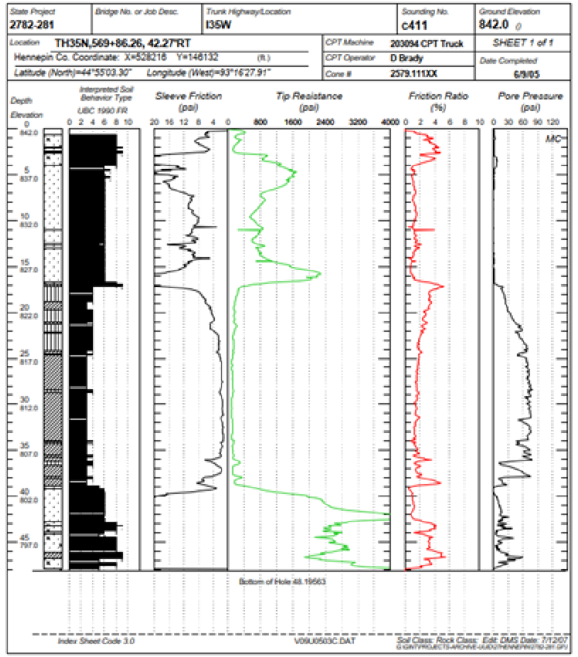
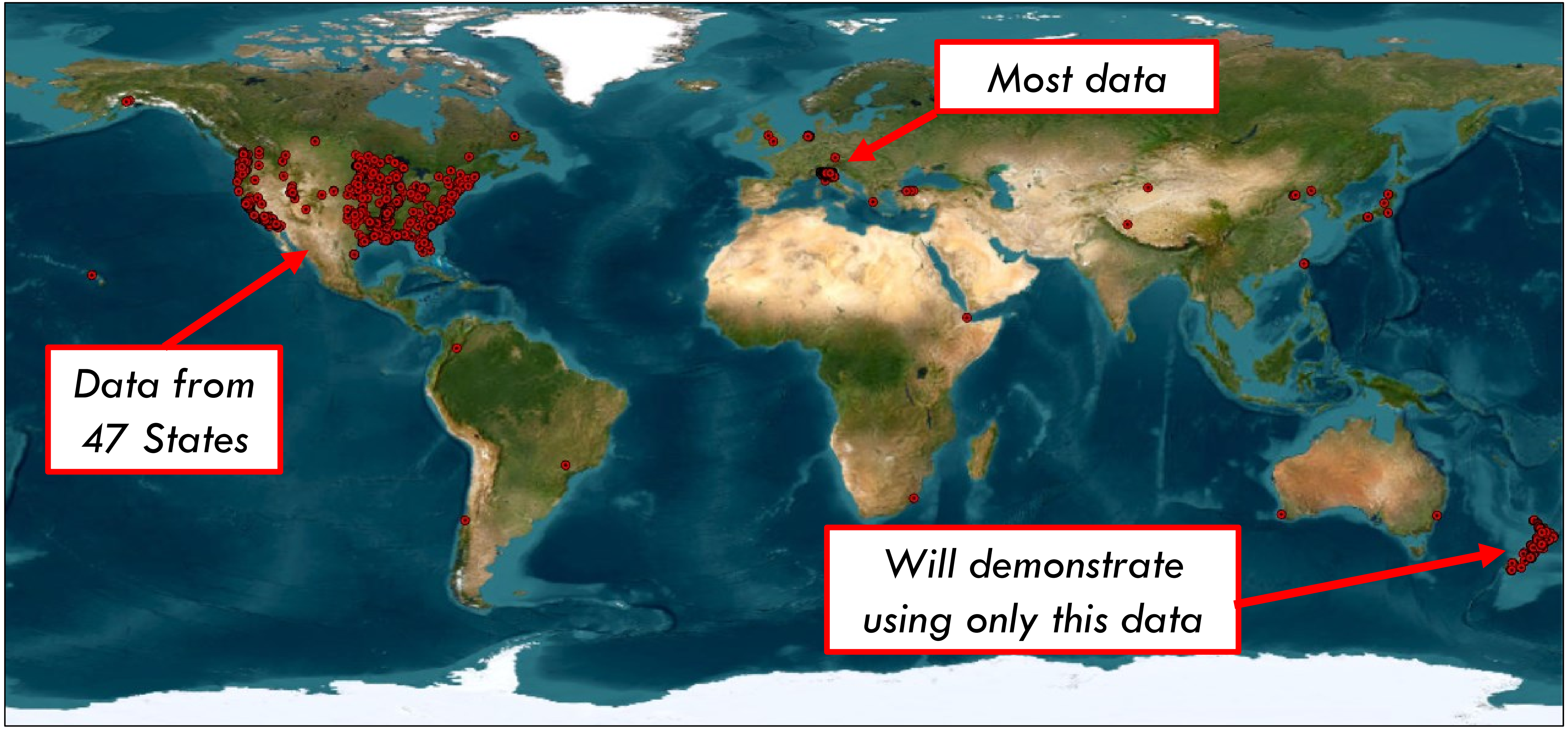
Modeling Concept & Demonstration in New Zealand

- ***Step 1/5**: Compile global subsurface geotechnical test data (we're using CPTs for now)*

CPT Data



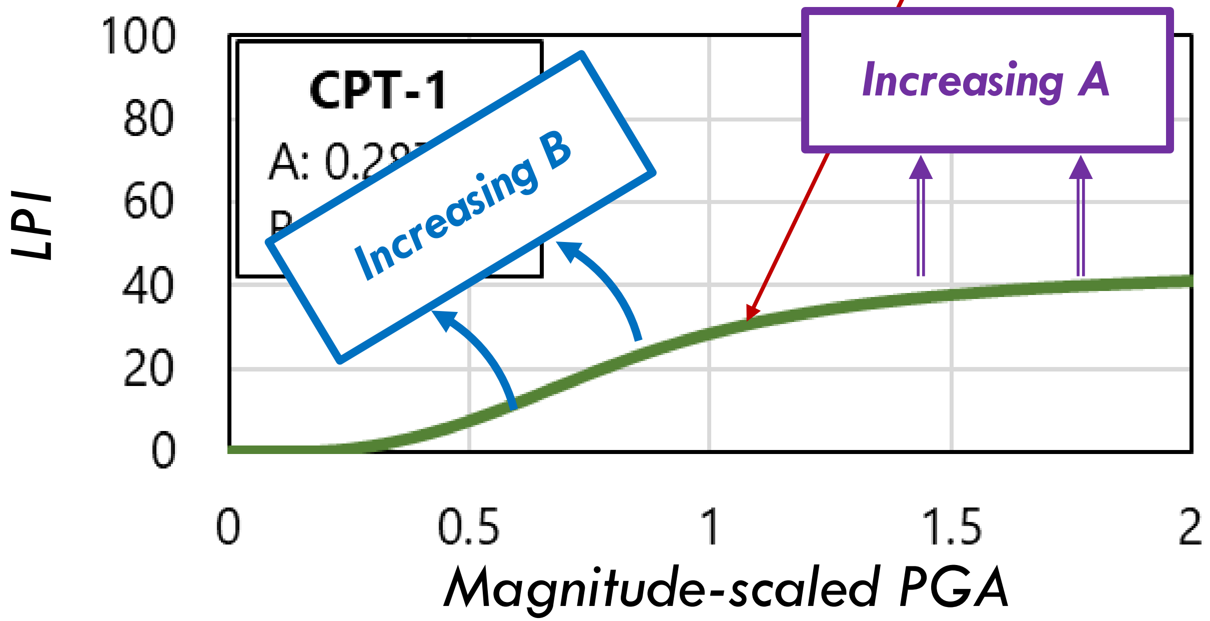
~45,000 CPTs and counting…



Modeling Concept & Demonstration in New Zealand

- ***Step 2/5**: Subject each CPT to a spectrum of seismic loading (PGA_M)*
  Predict liquefaction response (e.g., LPI) using Tier-2 models
  Fit functional form to this computed response

$$LPI = A\tan^{-1}\left(B * \left(PGA_M - \left(A/_B\right)\right)^2\right) * 100$$



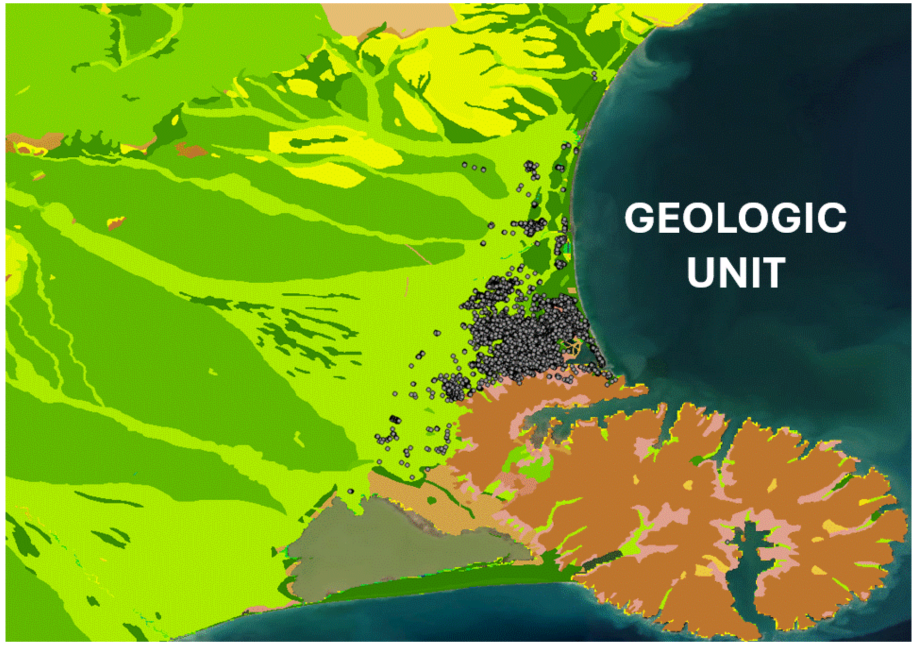
A conveys cumulative thickness of liquefiable strata

B conveys liquefaction resistance of those strata

Modeling Concept & Demonstration in New Zealand

➢ ***Step 3/5**: Compile geospatial features/predictors at CPT locations*

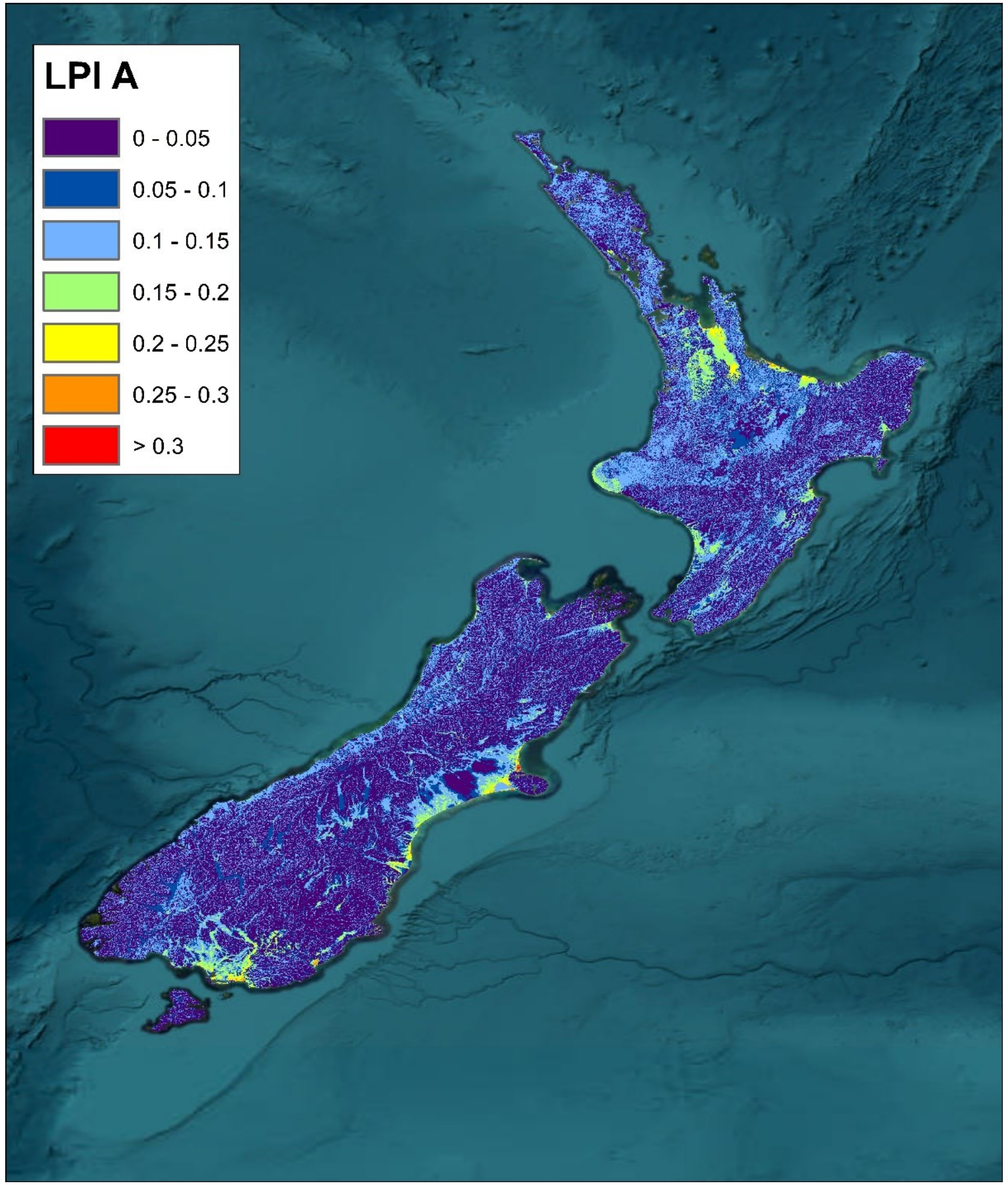
Variable	Description
Convergence	A classifying measure of convergent areas as channels and divergent areas as ridges.
Compound topographic index	A proxy of long-term soil moisture availability, also topographic wetness index.
Depth to bedrock	Interpolated depth to bedrock.
Distance to coast	Minimum distance to coast.
Distance to river	Minimum distance to river computed for different Strahler orders.
Elevation deviation	A measu
Geologic unit	Geology
Geomorphon	Classifie … r depression.
Groundwater depth	Interpola
Height above nearest drainage	A topogr … ainage network.
Landform entropy	A texture … ndow.
Landform uniformity	A texture
Major landform	The land … indow.
Maximum multiscale deviation	The diffe … n of the window.
Maximum multiscale roughness	The sphe … ruggedness.
Pfafstetter level	The 'Pfaf … basins.
Precipitation	Mean ar
Profile curvature	A measu … flow.
Roughness	The larg … ding cells.
Scale of MMD	See Max
Scale of MMR	See Max
Shannon index	A diversi … ow.
Soil depth	Qualitati
Soil drainage	Qualitati
Soil order	Soil classification consistent with the New Zealand Soil Classification (NZSC).
Tangential curvature	The rate of change perpendicular to a slope gradient; relates to sediment accumulation.
Terrain ruggedness index	A measure of the ruggedness and topographic complexity (elevation variability) of landscapes.
Topographic position index	The difference of elevation of a cell and the mean of its 8 surrounding cells.
Topographic slope	The rate of change of elevation in the direction of the water flow line.
Vector ruggedness measure	Quantifies ruggedness via variation in sine and cosine of the slope in three dimensions.
Vs30	Average shear wave velocity of uppermost 30m.

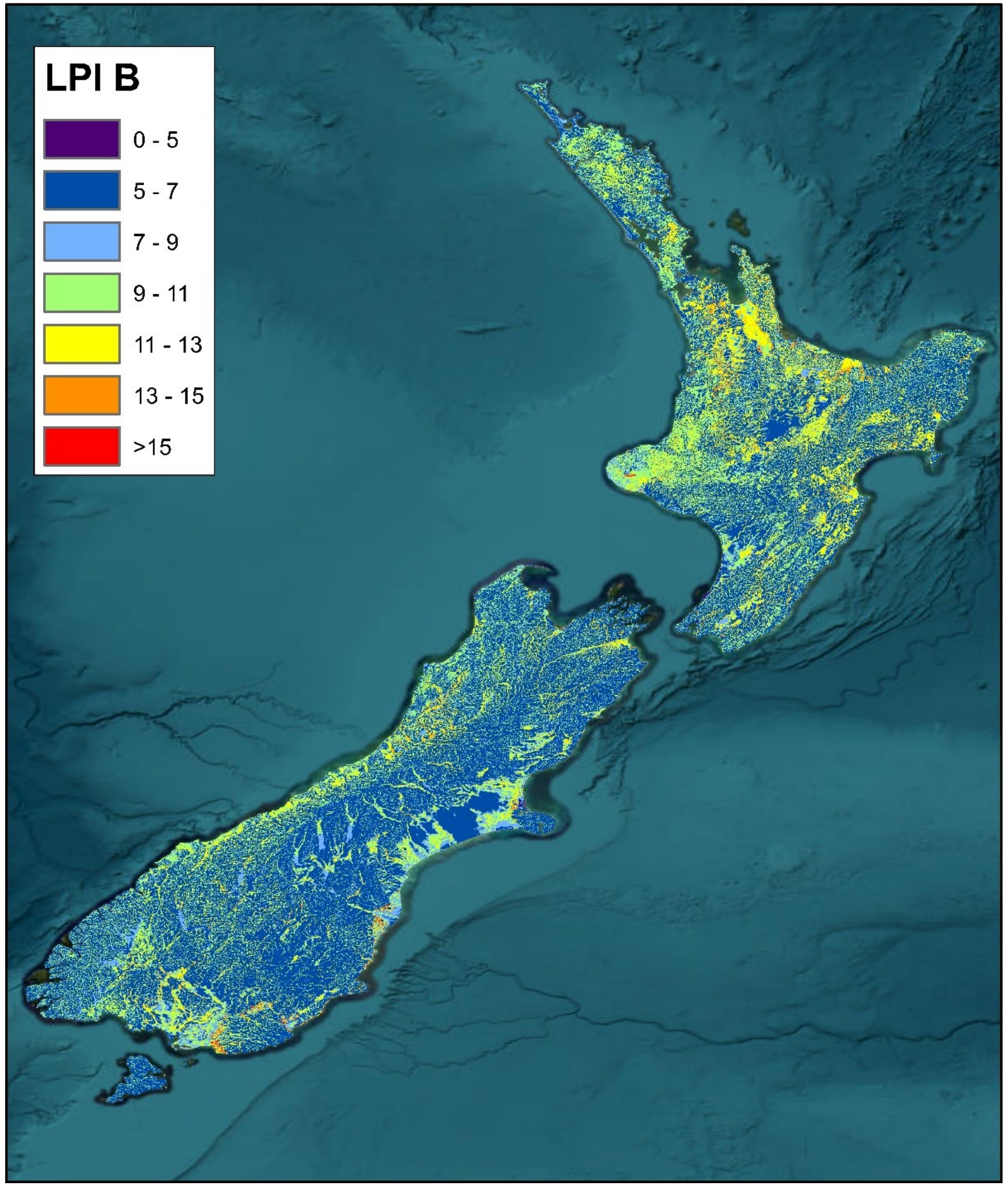


~75 global datasets

Modeling Concept & Demonstration in New Zealand

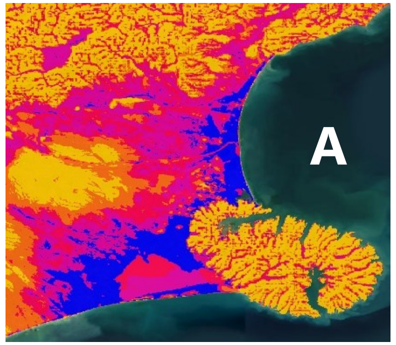
- ***Step 4/5****: Train ML model to predict A & B, then run models everywhere.*





Modeling Concept & Demonstration in New Zealand

- *Expected liquefaction response is, in effect, precomputed & stored everywhere on earth.*



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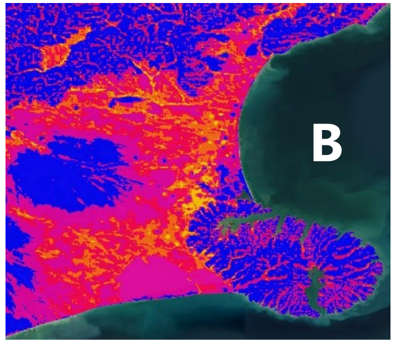
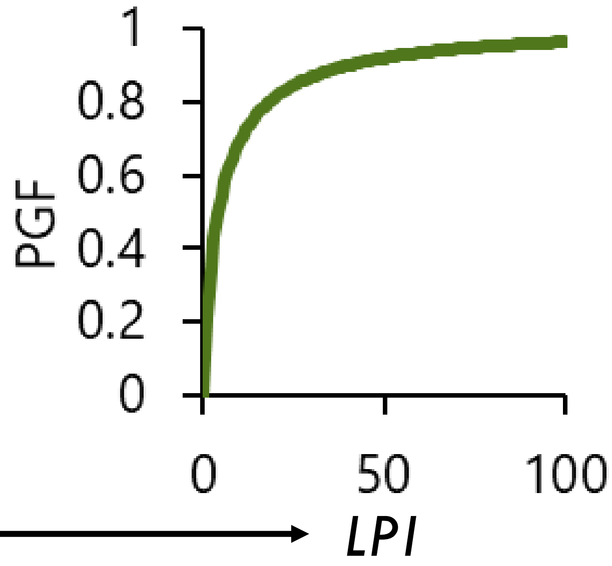
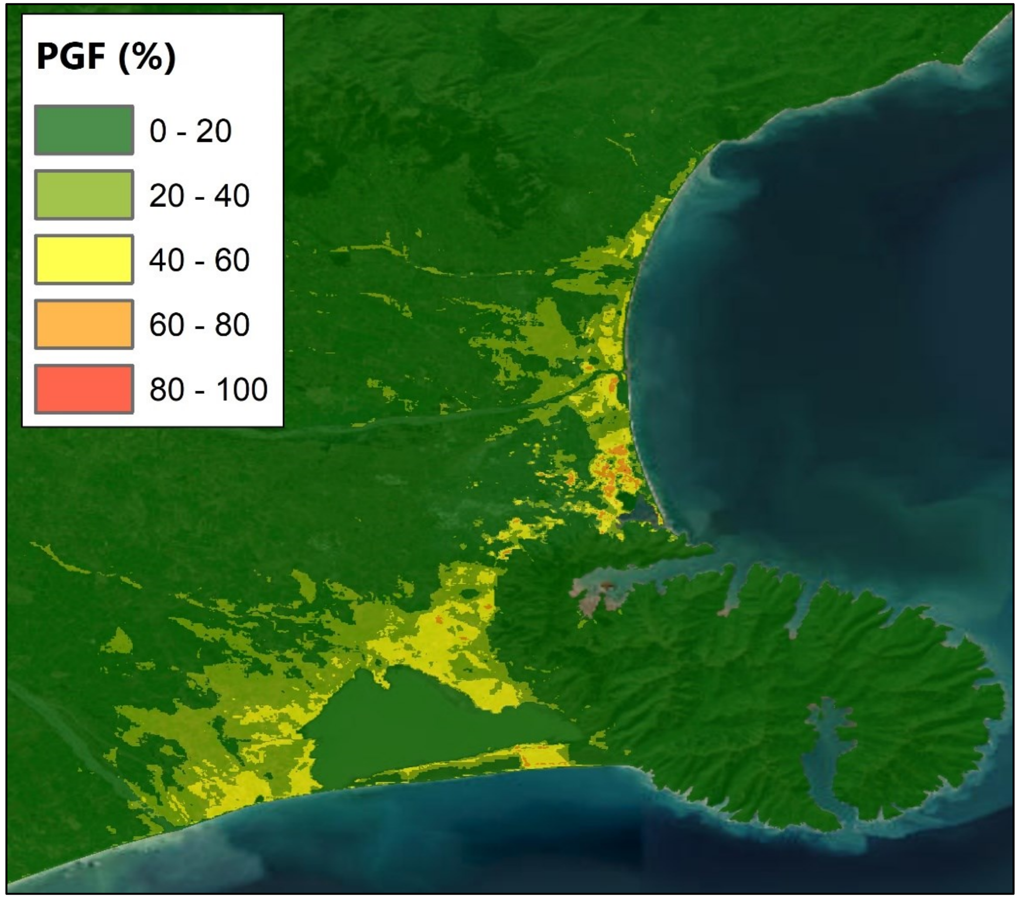




$$LPI = A\tan^{-1}\left(B * \left(PGA_M - \left(A/B\right)\right)^2\right) * 100$$

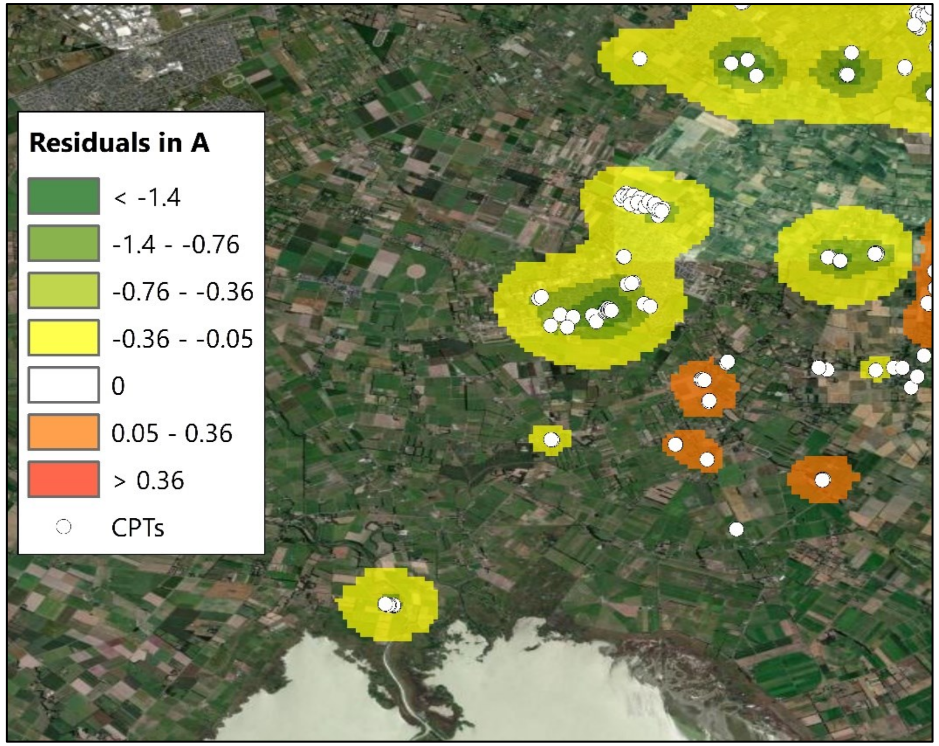


- *Permits rapid prediction of impacts (e.g., probability of ground failure, PGF).*

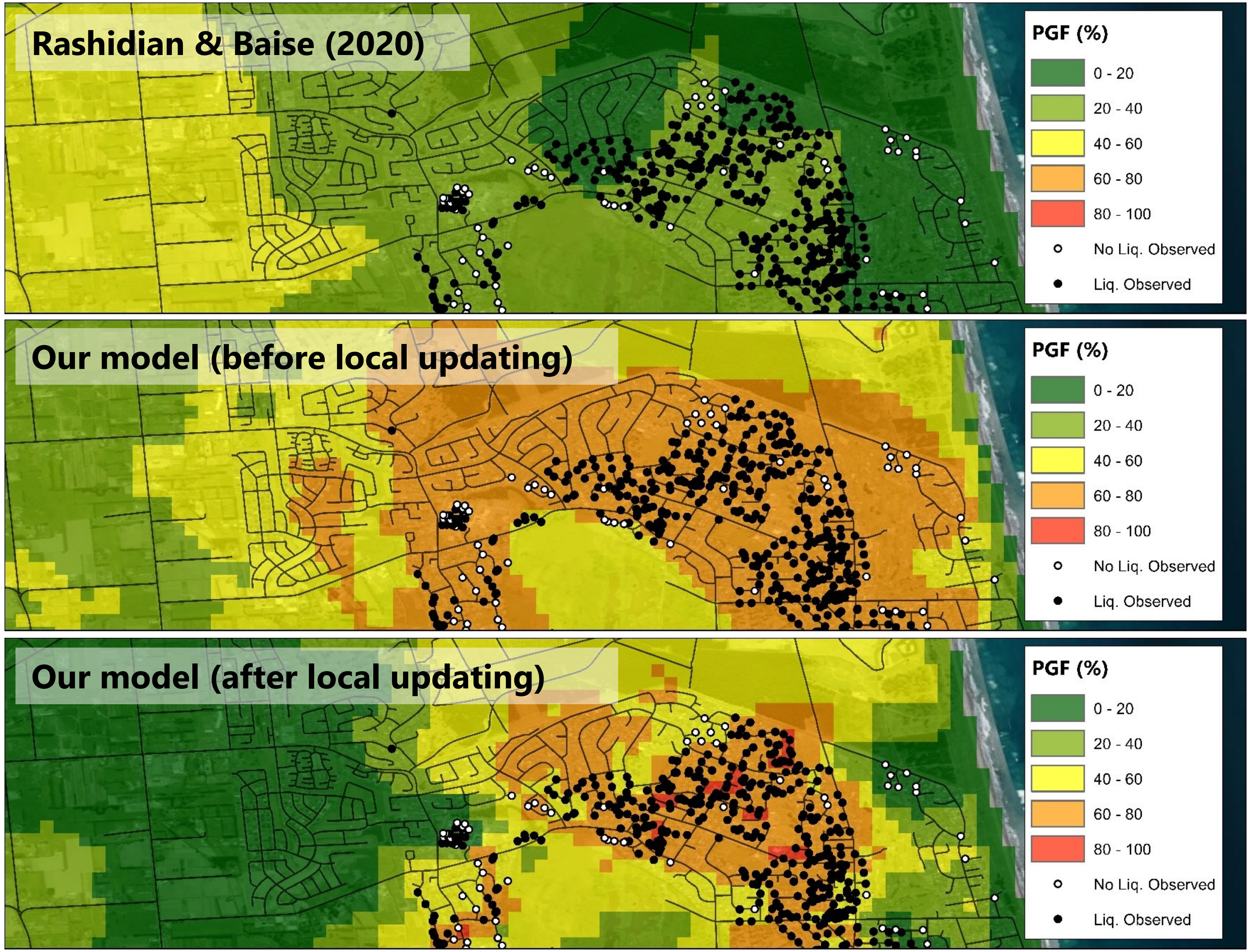
Modeling Concept & Demonstration in New Zealand

➢ **Step 5/5**: *ML predictions are geostatistically updated by geotechnical data*

$$A_{Residual} = ln \frac{A_{observed}}{A_{predicted}}$$



e.g., Feb 2011 M6.2 Christchurch Earthquake



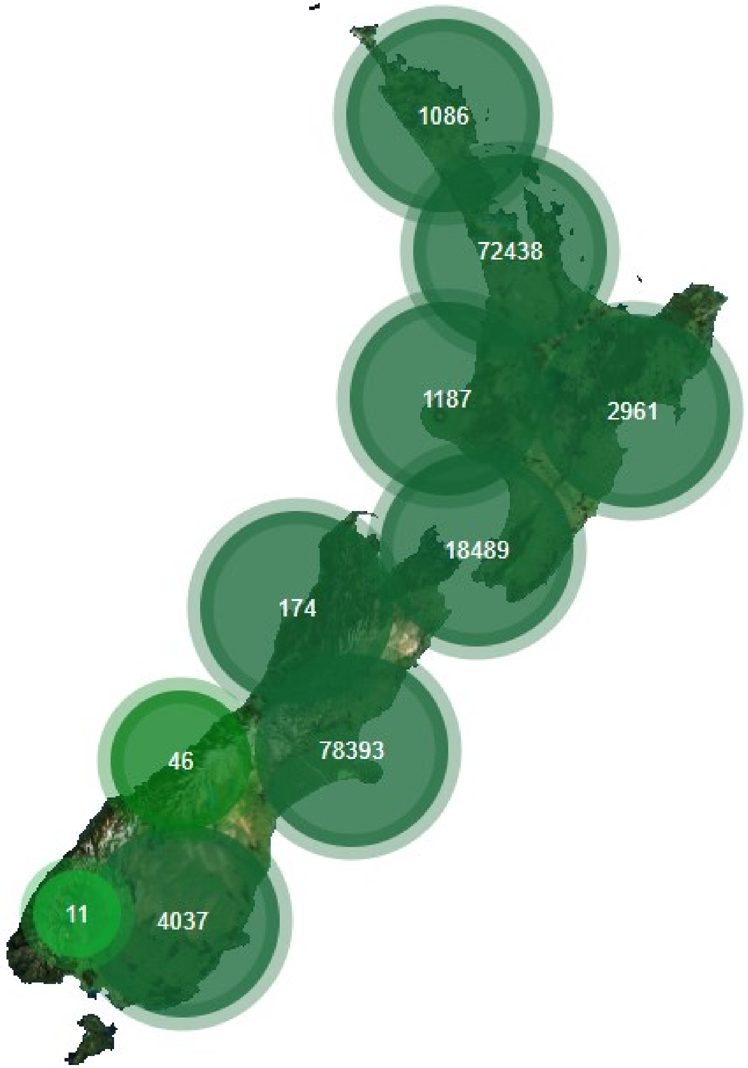
Outline

Motivation & Background — Goal — Model Concept/Demo — Benefits — Ongoing & Future Work

Benefits

- *Trains on subsurface measurements (vast training set), not on liquefaction case histories (small and slow to grow training set).*
- *ML can manage, exploit many potentially-useful predictors.*
- *Mechanics-informed (geotechnical backbone guides sensible response and scaling).*
- *Geostatistical updating anchors ML predictions to reality.*
- *Is <u>very</u> easy for end-users to implement, test, critique, etc.*
- *Will continuously improve with more data (global trend toward shared data)…*

New Zealand Geotechnical Database



100,000+ geotechnical explorations…

GEOLOGIC INFORMATION PORTAL

Washington DNR Data Portal

100,000+ geotechnical explorations…

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- *All code on GitHub; designed for frequent version updates with new community data.*

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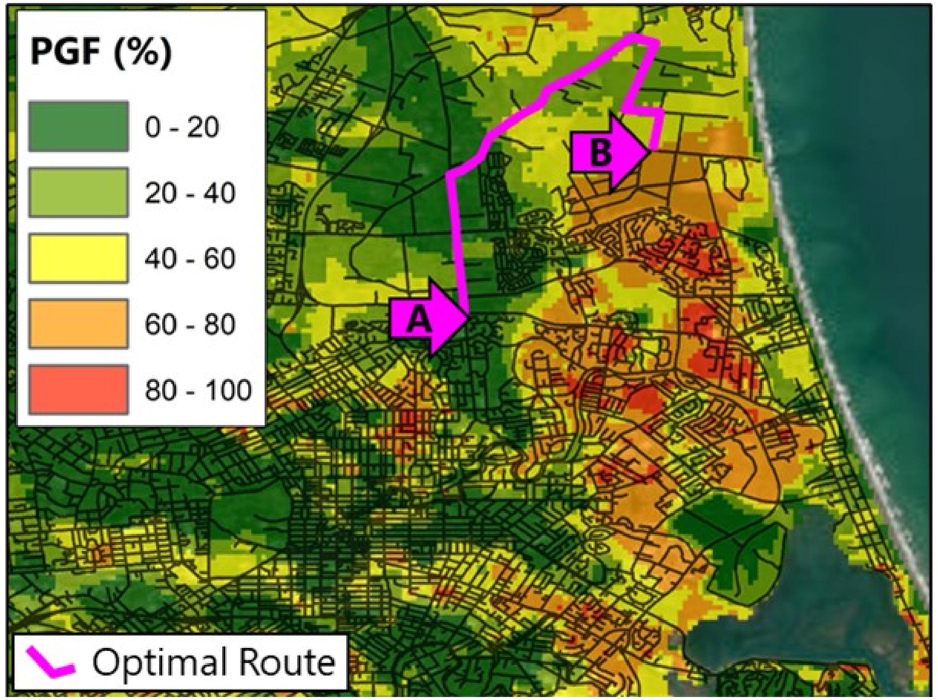
Ongoing and Future Work

- Data Intake, especially in PEER Territory (currently ~3,500 CPTs)
- Regional vs. National vs. Global Models
- Integration with SimCenter Tools (R2D)
- Network Modelling in Scenario Events
  - Merging with Bridge Damage (UW Structures)
  - Traffic Impacts
  - Access to HealthCare
  - Demographic Analyses



- Maps also permit PBEE analyses at regional scale (e.g., return period of damage)

Acknowledgements

PEER Support

Morgan Sanger, PhD Candidate, University of Washington

Mertcan Geyin, Norwegian Geotechnical Institute

Ryan Rasanen, University of North Carolina at Charlotte

Marc Eberhard, University of Washington

Pedro Arduino, University of Washington

REFERENCES

Maurer, B.W. and Sanger, M.D. (2023). "Why 'AI' Models for Predicting Liquefaction have been Ignored, Plus some that Shouldn't Be." *Earthquake Spectra*, 39(3): 1883-1910.

Rasanen, R.A., Geyin, M., and Maurer, B.W. (2023). "Select Liquefaction Case Histories from the 2001 Nisqually, Washington Earthquake: A Digital Dataset and Assessment of Model Performance." *Earthquake Spectra*, 39(3): 1534-1557.

Geyin, M. and Maurer, B.W. (2023). "U.S. National VS30 Models and Maps Informed by Remote Sensing and Machine Learning." *Seismological Research Letters,* 94(3): 1467-1477.

Geyin, M., Maurer, B.W., and Christofferson, K. (2022). "An AI Driven, Mechanistically-Grounded Geospatial Liquefaction Model for Rapid Response and Scenario Planning." *Soil Dynamics and Earthquake Engineering,* 159: 107348, Elsevier.

Geyin, M. and Maurer, B.W. (2020). "Fragility functions for liquefaction-induced ground failure." *Journal of Geotechnical and Geoenvironmental Engineering,* 146(12): 04020142, ASCE.

Green, R.A., Bommer, J.J., Stafford, P.J., Maurer, B.W., Kruiver, P.P., Edwards, B., Rodriguez-Marek, A., de Lange, G., Oates, S.J., Storck, T., Omidi, P., Bourne, S.J., and van Elk, J.F. (2020). "Liquefaction hazard of the Groningen region of the Netherlands due to induced seismicity." *Journal of Geotechnical and Geoenvironmental Engineering,* 146(8): 04020068, ASCE.

Geyin, M., Baird, A.J., and Maurer, B.W. (2019). "Field assessment of liquefaction prediction models based on geotechnical vs. geospatial data, with lessons for each." *Earthquake Spectra,* 36(3): 1386–1411, Earthquake Eng. Research Institute.