LIQUEFACTION HAZARD ASSESSMENT: LESSONS OLD AND NEW FROM THE CANTERBURY EARTHQUAKE SEQUENCE

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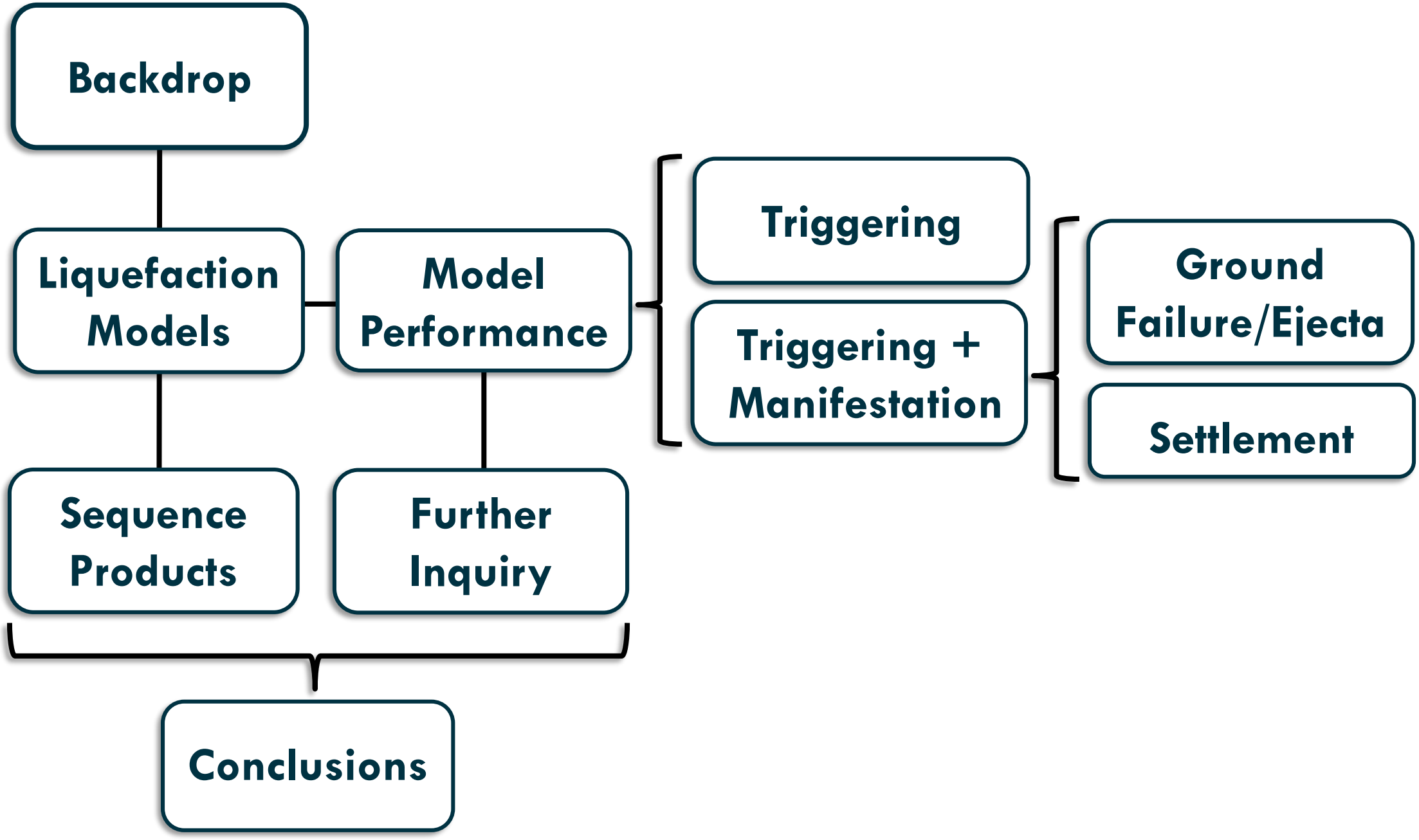
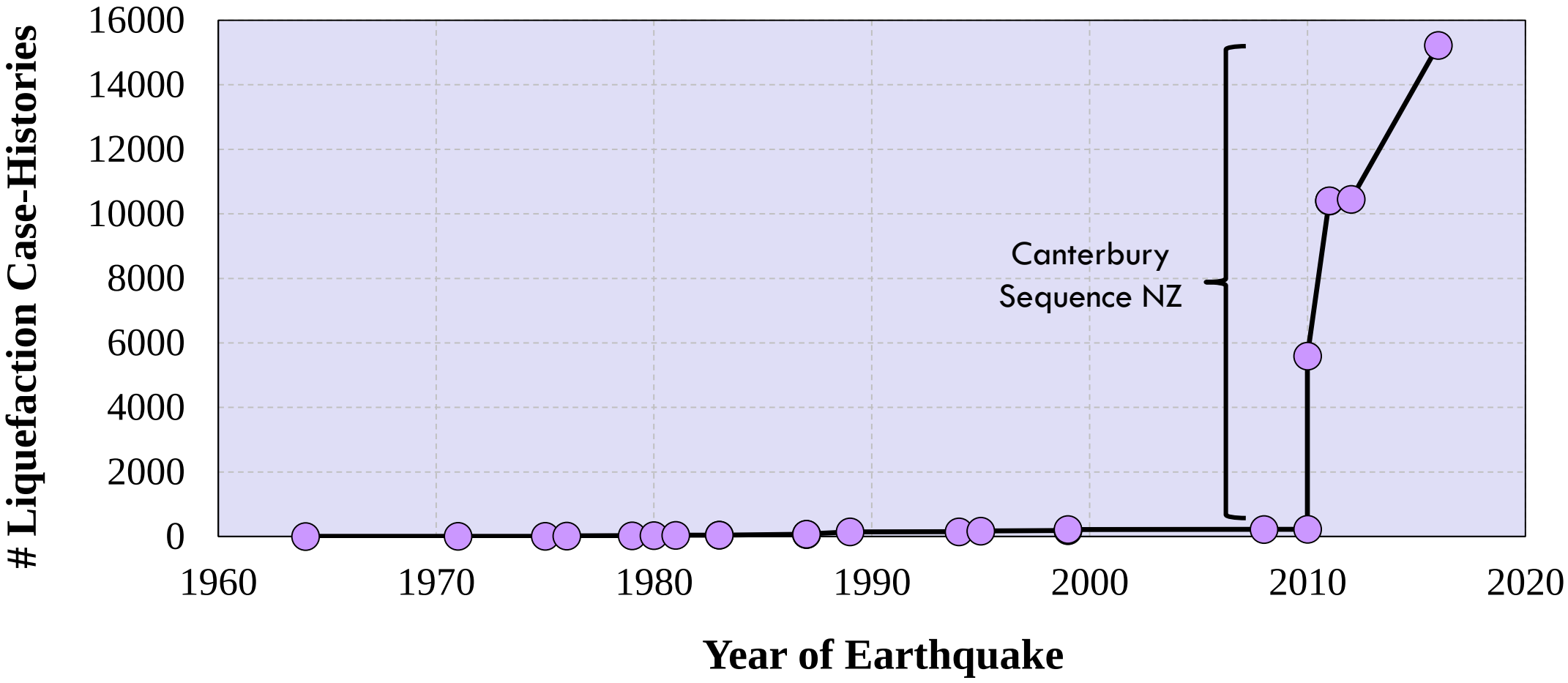
OUTLINE


Backdrop
Liquefaction Models
Model Performance
Triggering
Triggering + Manifestation
Ground Failure/Ejecta
Settlement
Sequence Products
Further Inquiry
Conclusions

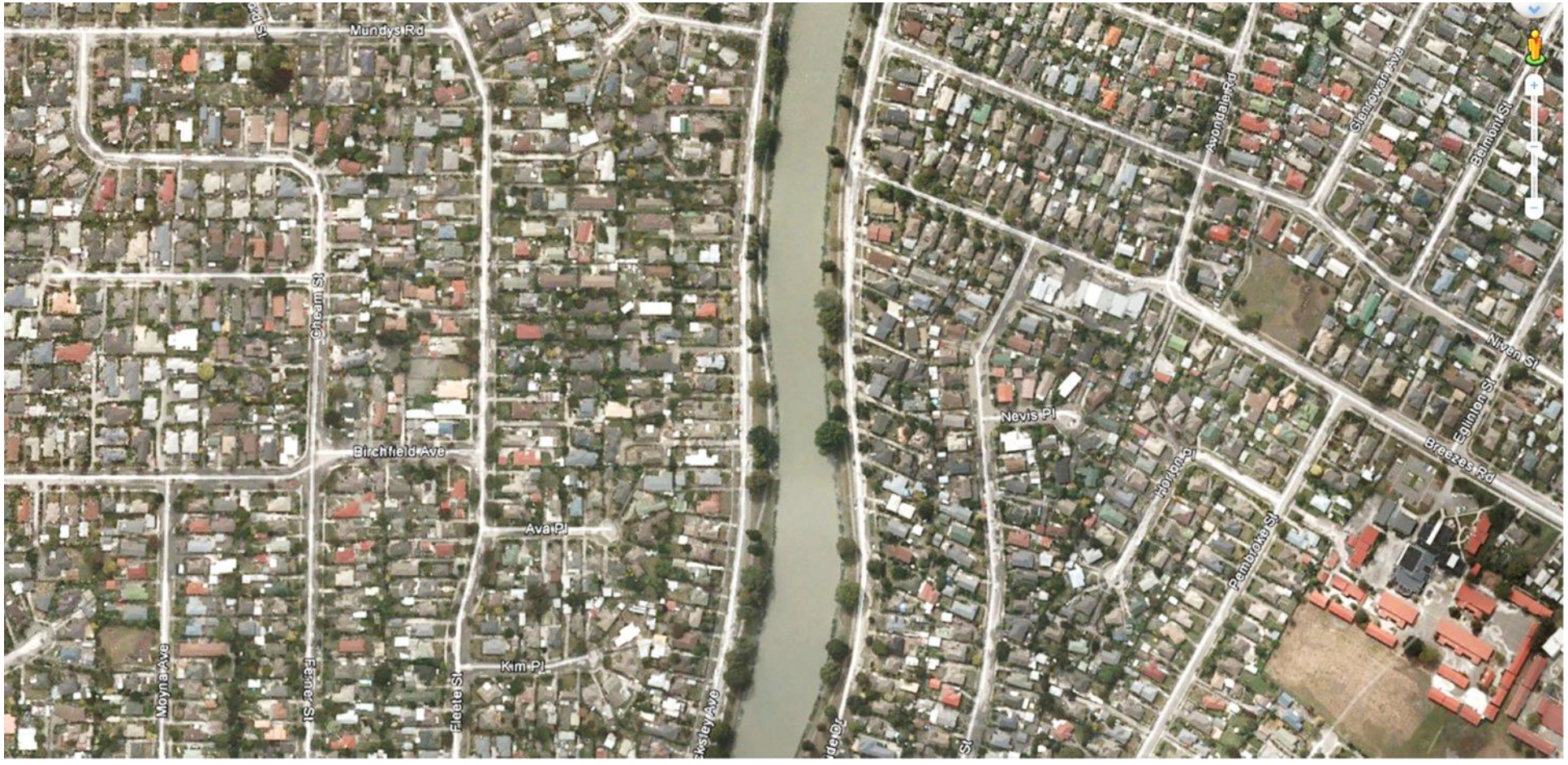
Backdrop

Cumulative compilation of CPT-based liquefaction case-histories



Backdrop

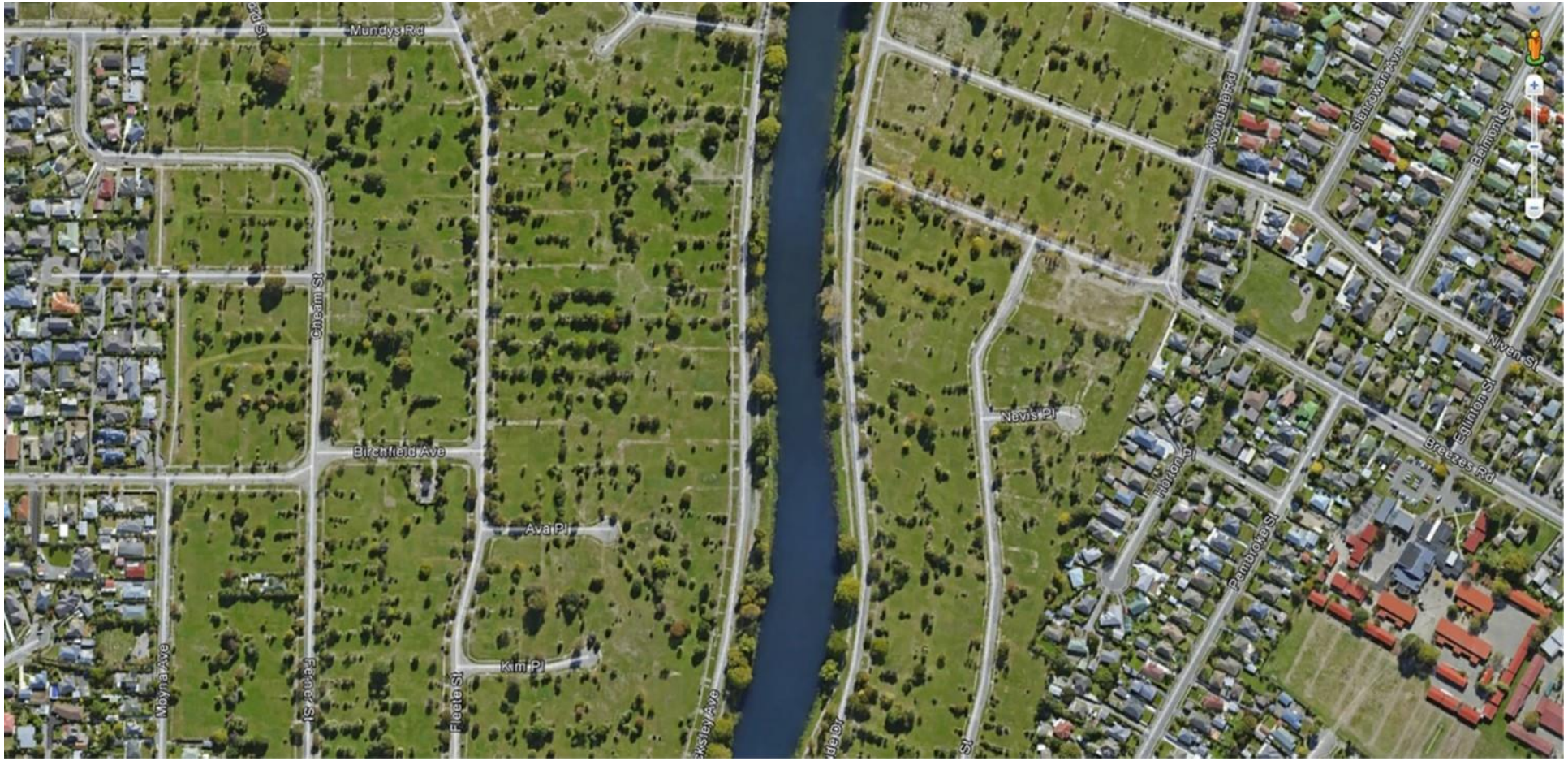
Christchurch, New Zealand



Before Canterbury Earthquake Sequence (2010)

Backdrop

Christchurch, New Zealand

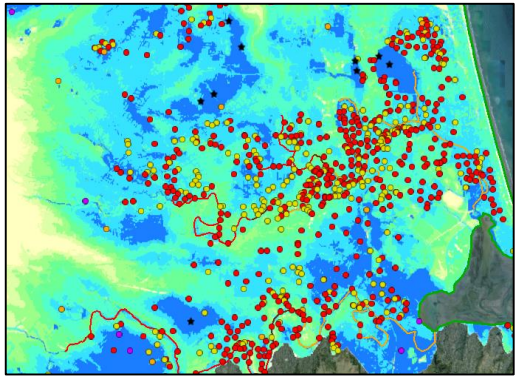


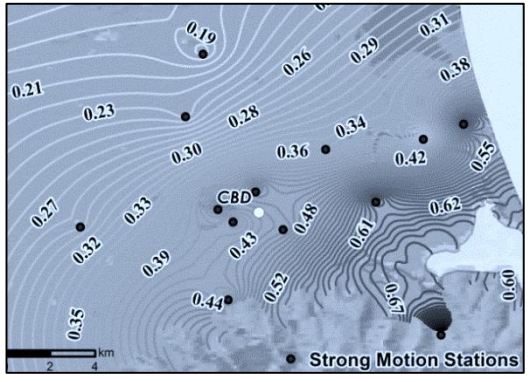
After Canterbury Earthquake Sequence (2017)

Backdrop

A beneficial outcome…

Airborne LIDAR and high resolution imagery following multiple earthquakes	Ground water measurements from 1,000+ piezometers	25,000+ cone penetration tests (CPTs) to characterize subsurface	Recordings from 20 strong motion stations across Christchurch in multiple earthquakes





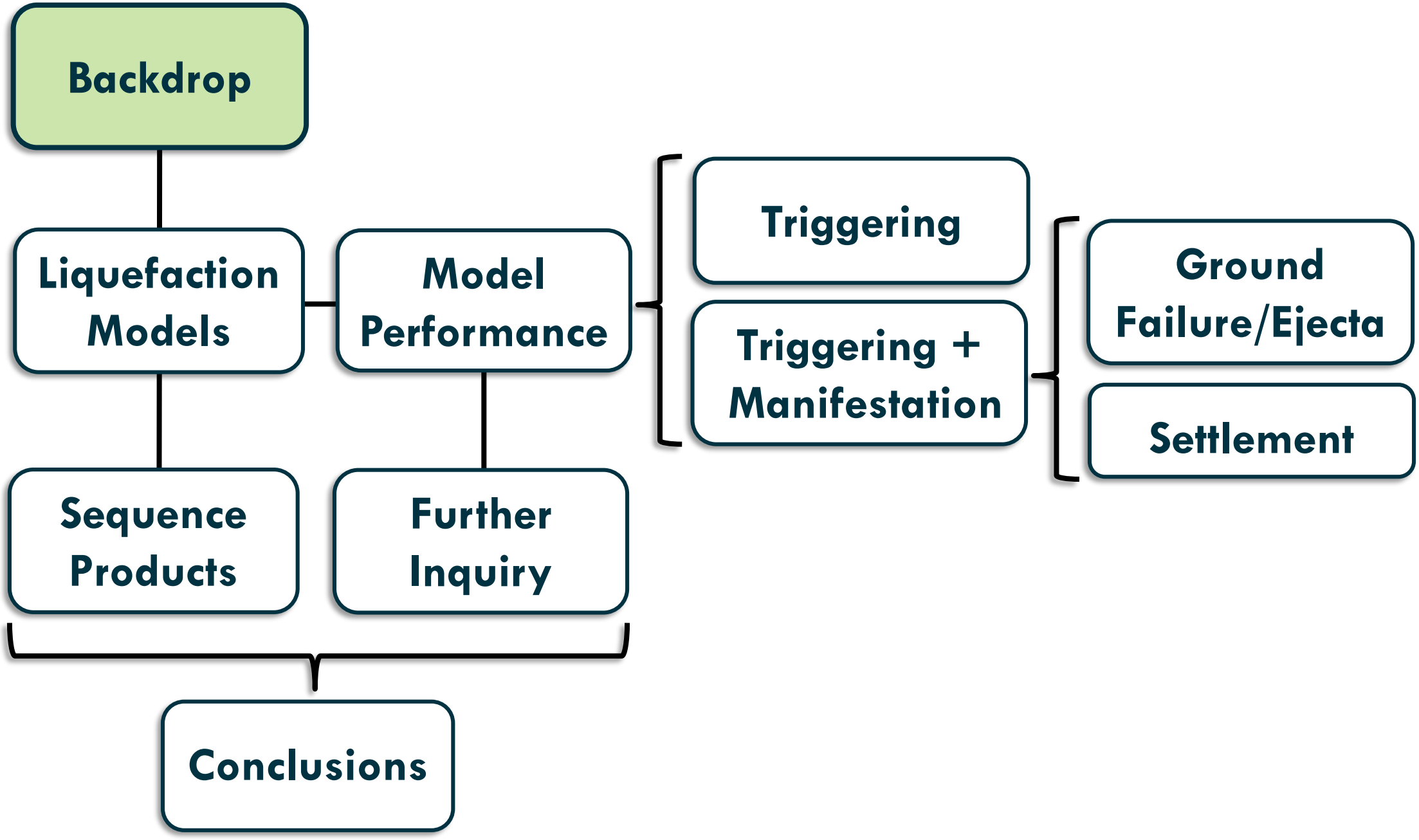
High-quality bulk ingredients for liquefaction case-histories

Backdrop

Year	Earthquake	Country	Magnitude	# Case Histories
1964	Niigata	Japan	7.60	3
1971	San Fernando	USA	6.60	2
1975	Haicheng	China	7.00	2
1976	Tangshan	China	7.60	10
1979	Imperial Valley	USA	6.53	7
1980	Victora (Mexicali)	Mexico	6.33	5
1981	Westmoreland	USA	5.90	9
1983	Nihonkai-Chubu	Japan	7.70	2
1983	Borah Peak	USA	6.88	3
1987	Edgecumbe	New Zealand	6.60	23
1987	Elmore Ranch	USA	6.22	2
1987	Superstition Hills	USA	6.54	8
1989	Loma Prieta	USA	6.93	67
1994	Northridge	USA	6.69	3
1995	Hyogoken-Nambu	Japan	6.90	21
1999	Kocaeli	Turkey	7.51	16
1999	Chi-Chi	Taiwan	7.62	34
2008	Achaia-Ilia	Greece	6.40	2
2010	El Mayor-Cucapah	Mexico	7.20	3
2010	Darfield	New Zealand	7.10	5371
2011	Christchurch	New Zealand	6.20	4806
2011	Tohoku	Japan	9.00	7
2012	Emilia	Italy	6.10	45
2016	Christchurch	New Zealand	5.70	4771
			Total	**15,222**

…unprecedented data to test/improve liquefaction analytics

OUTLINE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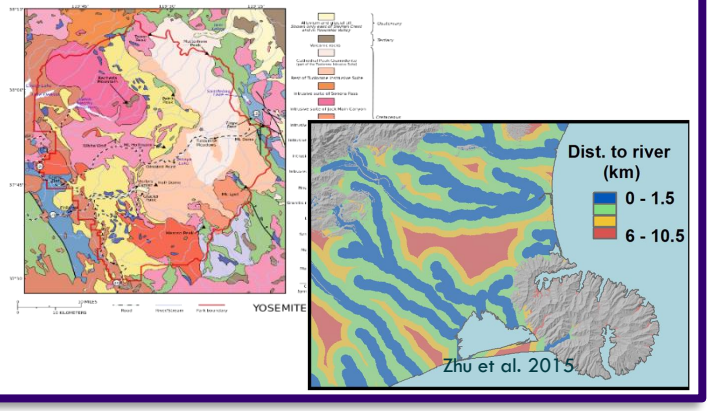
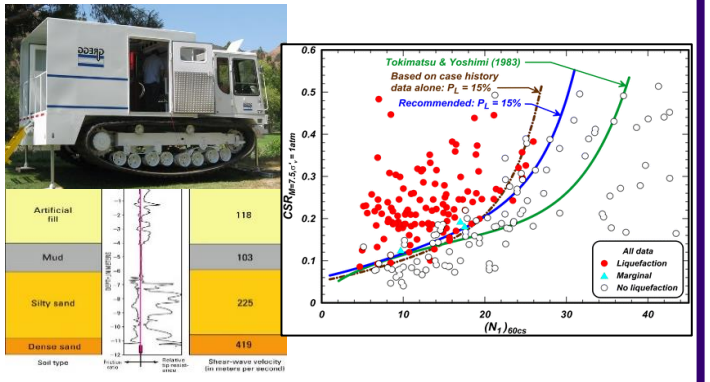
Models for Predicting Liquefaction Occurrence/Consequence

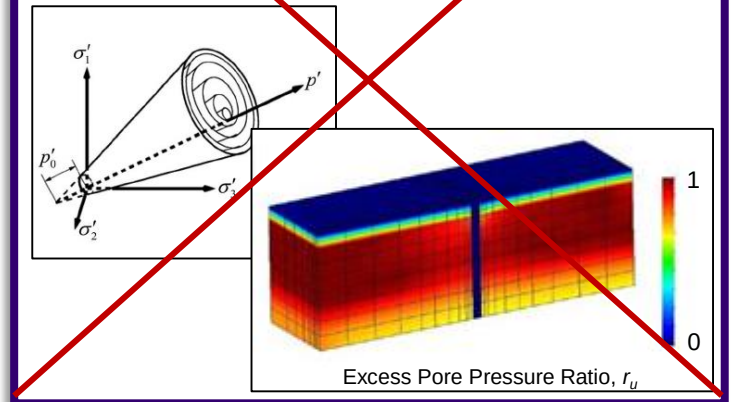
Tier 1
Geologic/Geospatial Models



Tier 2
"Simplified Stress-Based" Models



Tier 3
Numerical/Constitutive Models



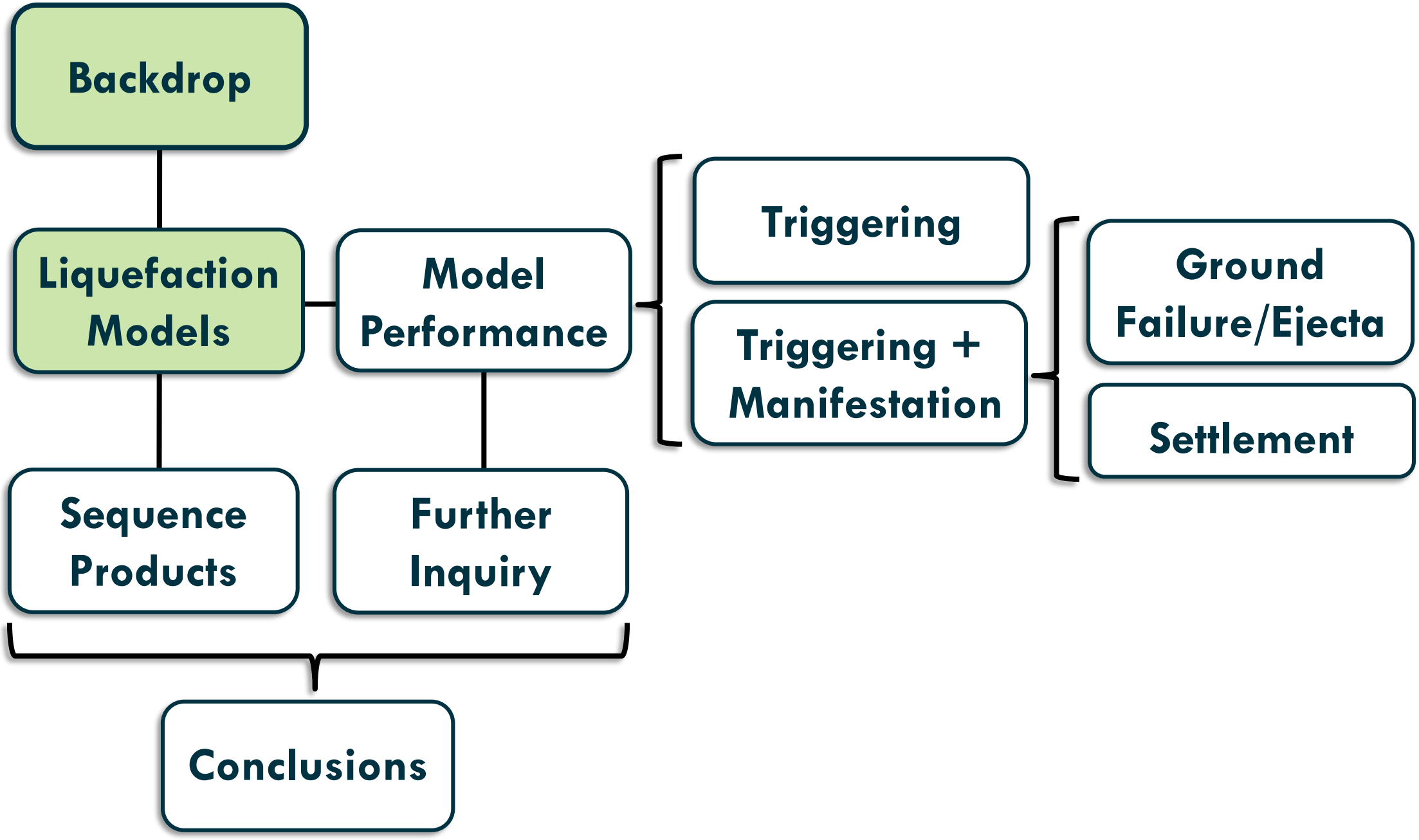
Increasing Cost/Complexity

(T1) Wholly-empirical models requiring only free geologic or geospatial data

(T2) Semi-mechanistic "simplified" models requiring in-situ test measurements

~~**(T3)** Wholly-mechanistic constitutive models requiring many parameters~~

OUTLINE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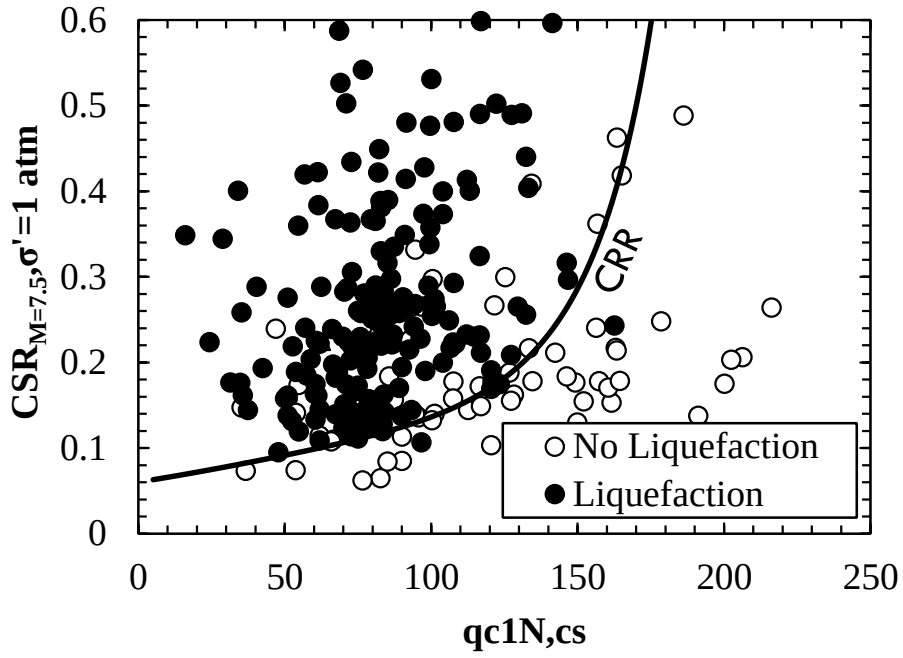
"Tier 2" Geotechnical Triggering Models

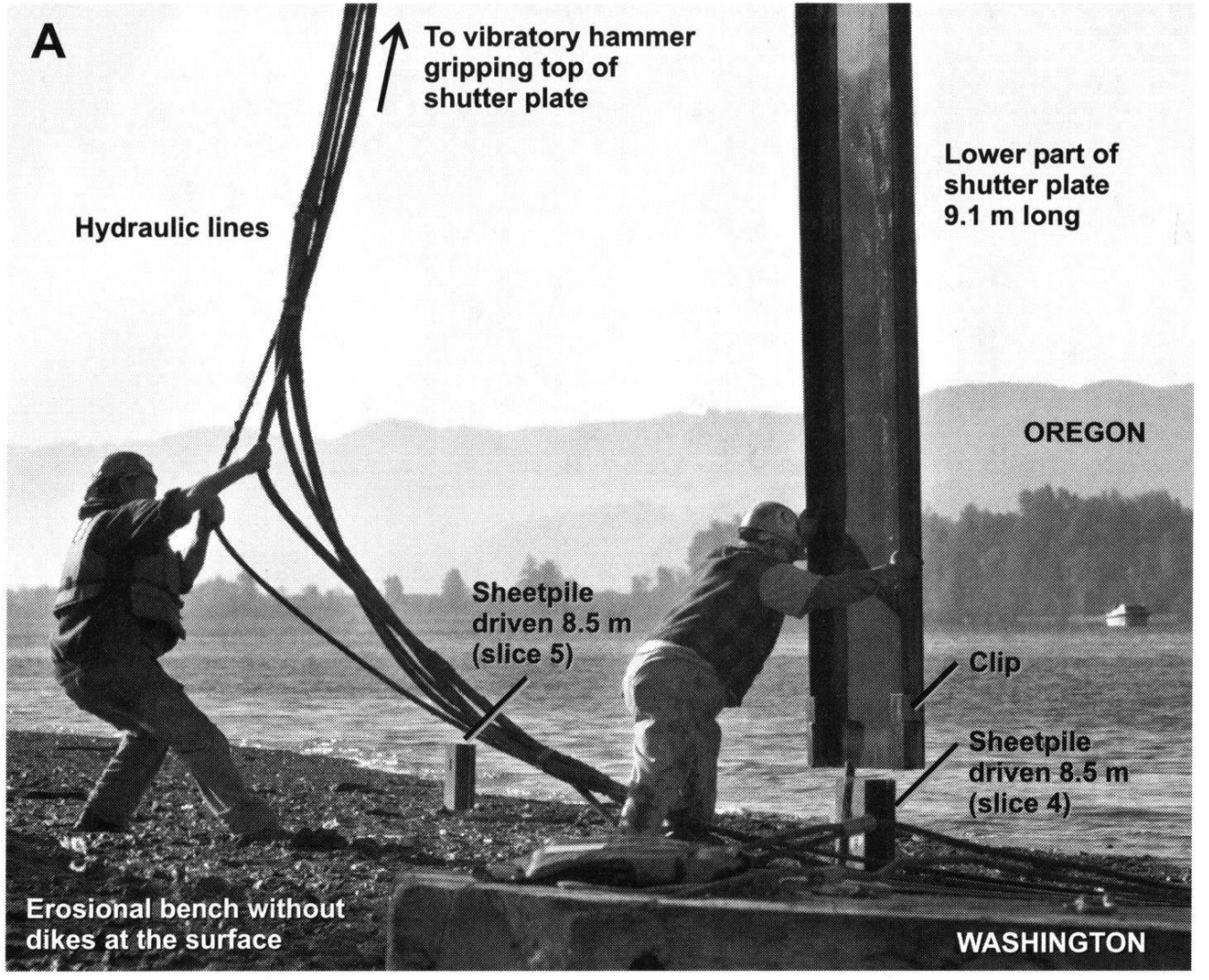
- Let's evaluate six triggering models:

1) Robertson & Wride (1998): **RW98**
2) Architectural Inst. Japan (2001): **AIJ01**
3) Moss et al. (2006): **Mea06**
4) Idriss & Boulanger (2008): **IB08**
5) Boulanger and Idriss (2014): **BI14**
6) Green et al. (2018): **Gea18**

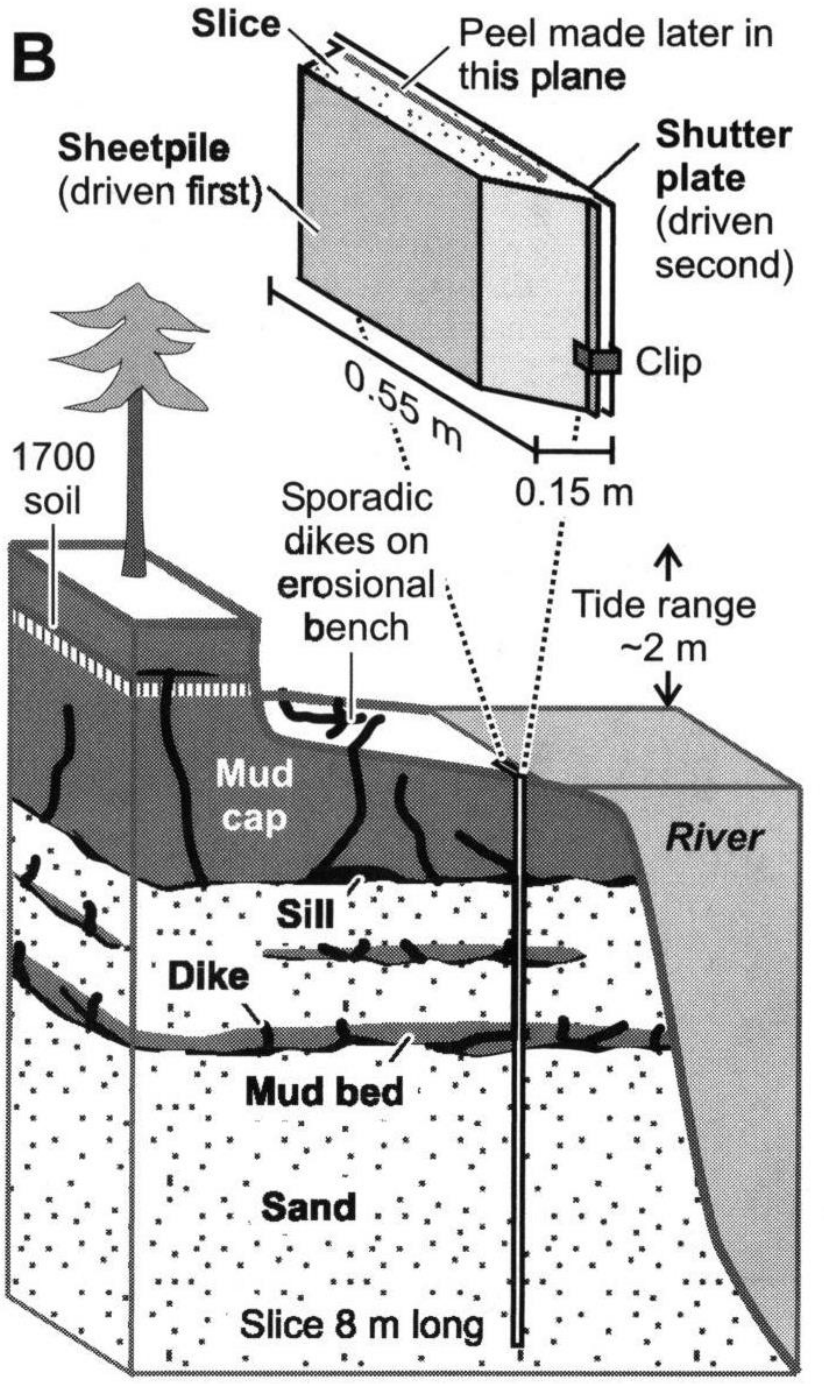


- Is there an objective and practical way to evaluate performance?
  - No
  - How to compare predictions w/ observations in numerous strata?
    - Inferences via "critical layer" (too subjective)
    - Down-hole PPT arrays (too few)
    - Geoslices (too expensive)

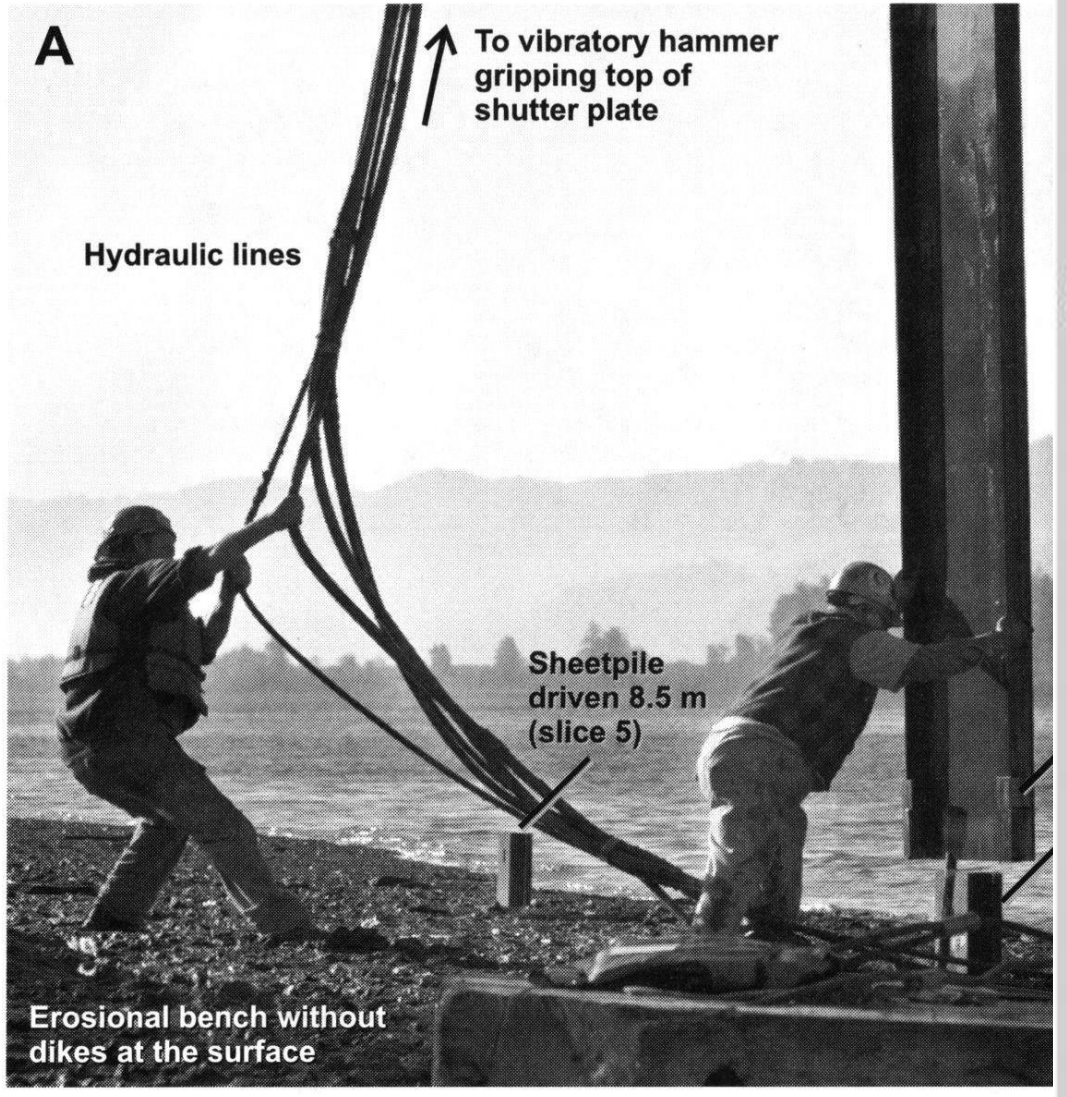
Geoslice



Takada and Atwater (2004)



Geoslice



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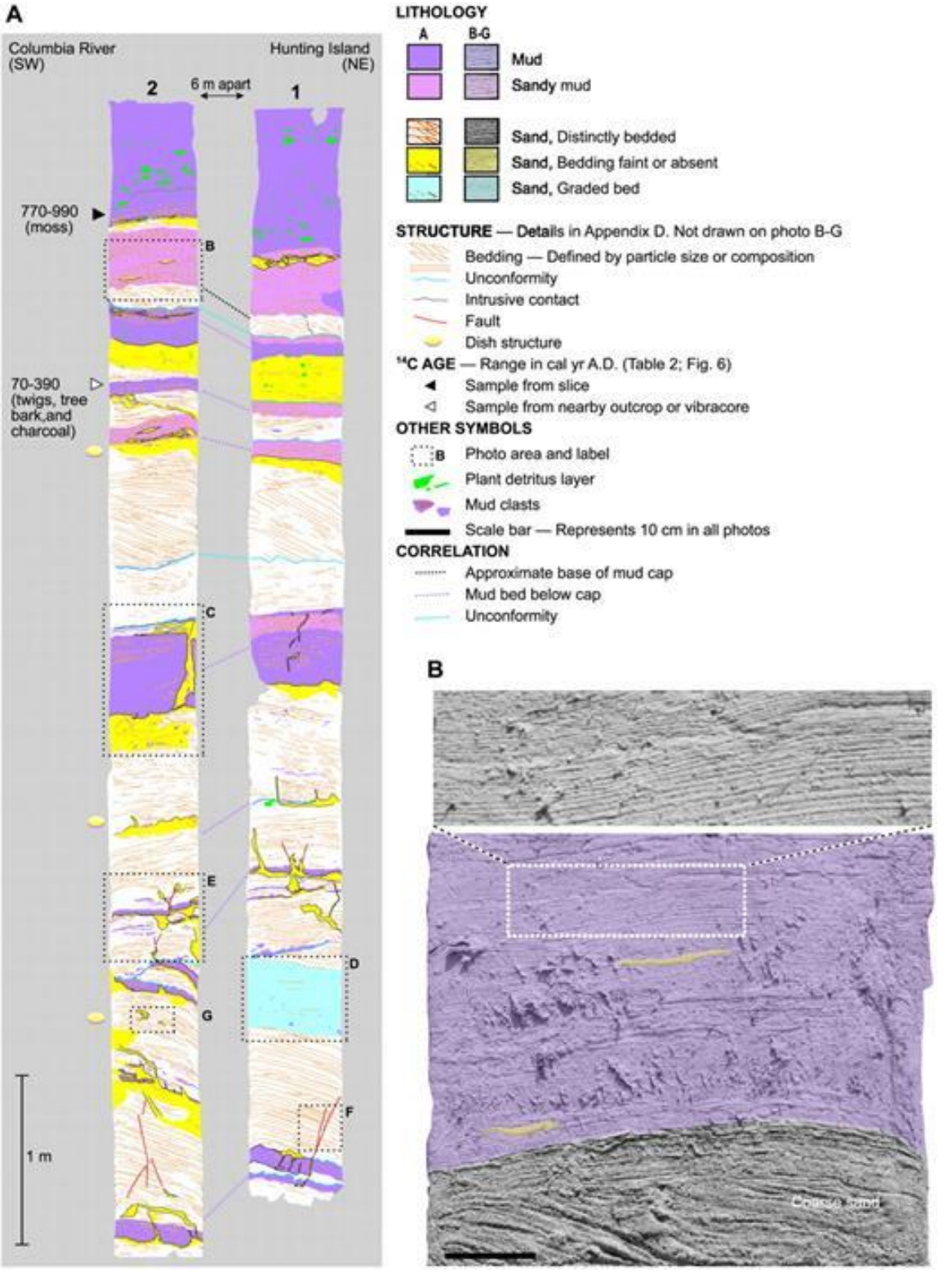

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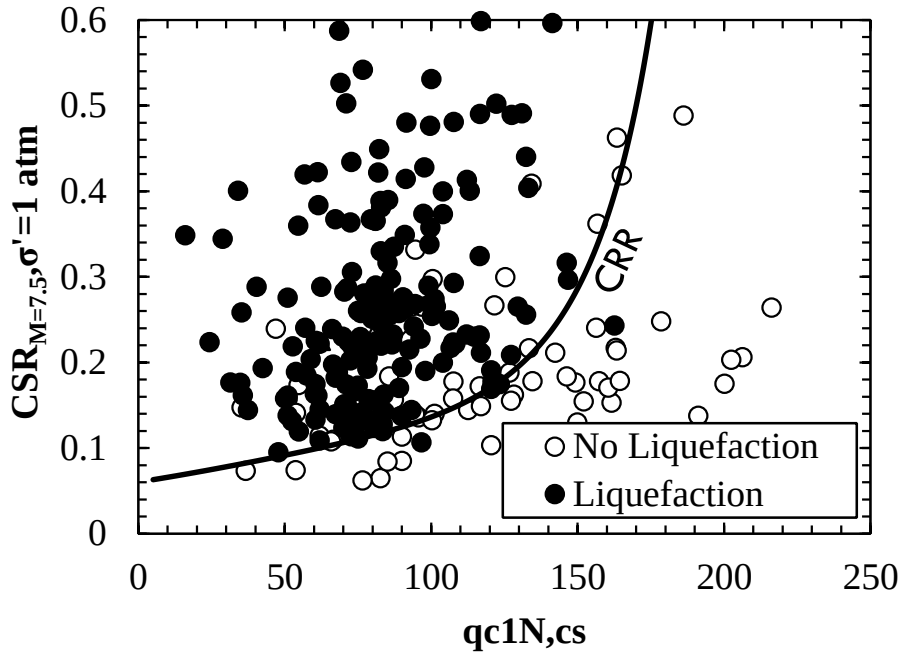

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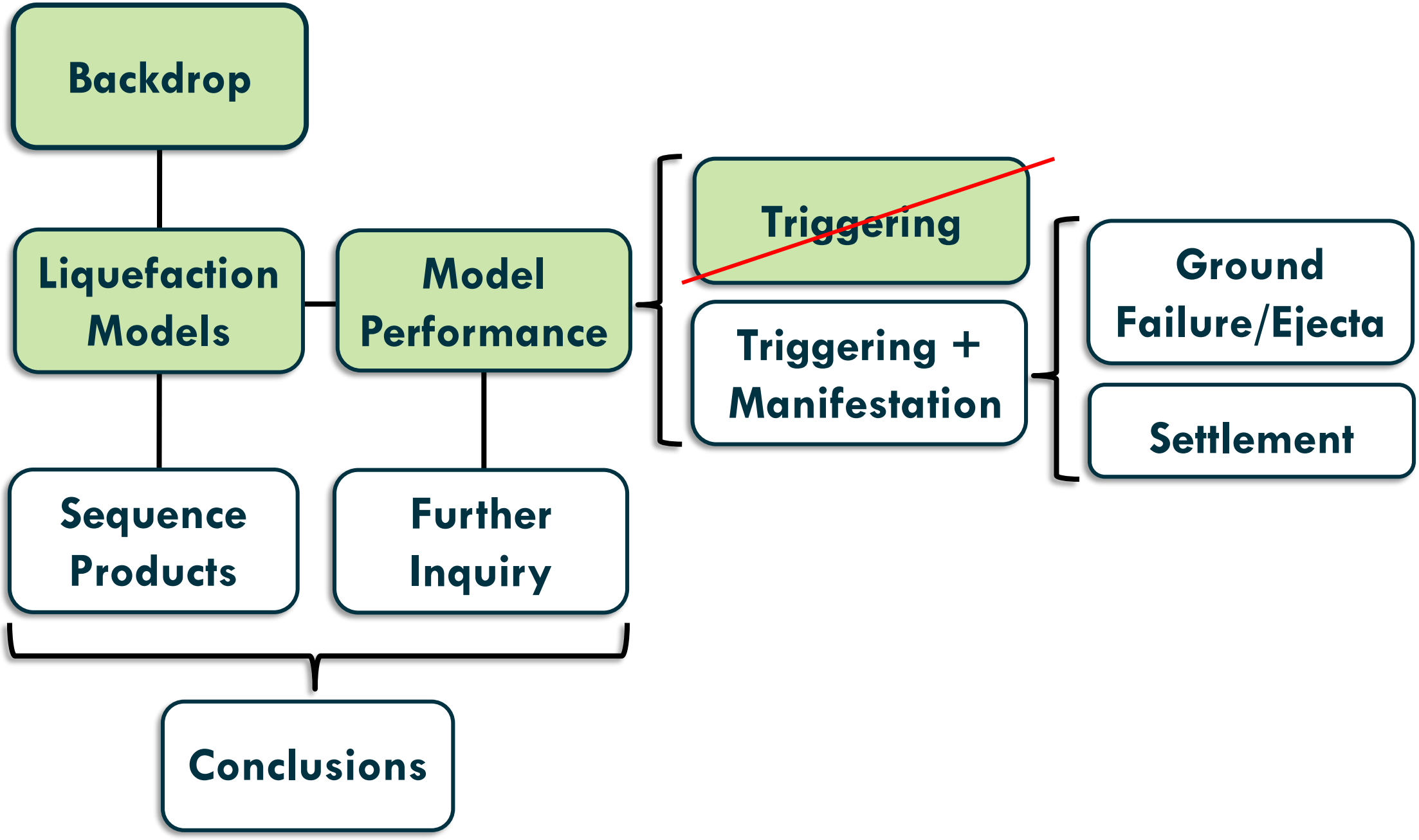
  - How to compare predictions w/ observations in numerous strata?
    - Inferences via "critical layer" (too subjective)
    - Down-hole PPT arrays (too few)
    - Geoslices (too expensive)
  - **For 99% of cases, we only have ground-surface observations**

OUTLINE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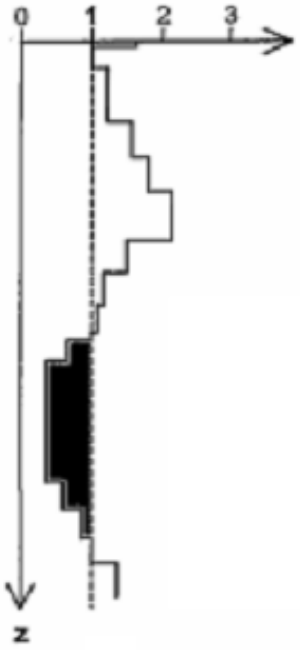
"Tier 2" Geotechnical Triggering + Manifestation Models

- Use of triggering model and manifestation model in sequence

Liquefaction Triggering Model + Liquefaction Manifestation Model

Robertson & Wride (1998)
Arch. Inst. Japan (2001)
Moss et al. (2006)
Idriss & Boulanger (2008)
Boulanger & Idriss (2014)
Green et al. (2018)

FS_{liq}



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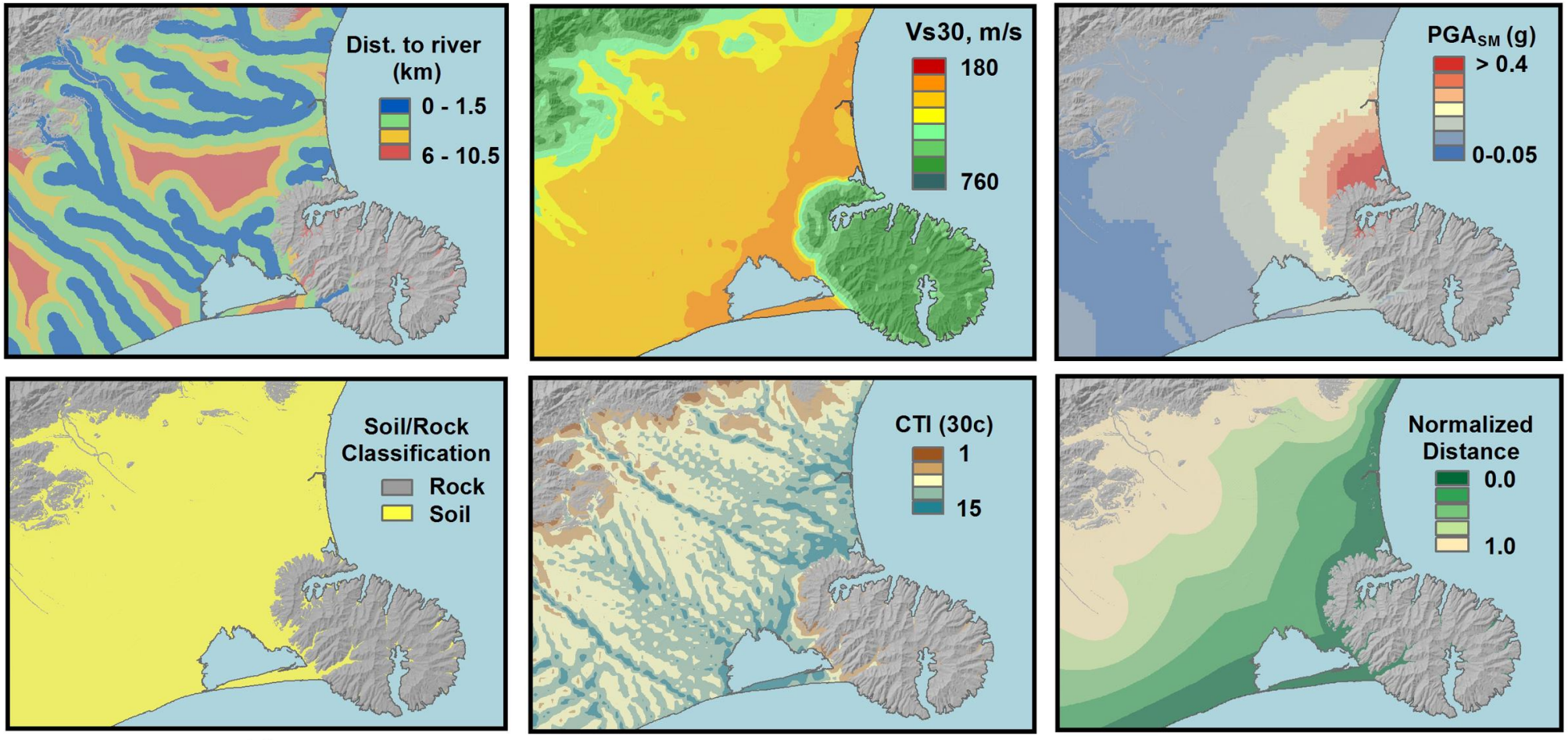
- ΔH — Zhang et al. (2002) — **Settlement**
- LPI — Iwasaki et al. (1978) — **Ejecta**
- LPI_{ISH} — Maurer et al. (2015) — **Ejecta**
- LSN — van Ballegooy et al. (2014) — **Ejecta**

Compare to Observations

"Tier 1" Geospatial Triggering + Manifestation Models

- Use readily-available free geospatial data (no in-situ testing)
- Subsurface properties relevant to liquefaction (e.g. soil density, saturation) are inferred from satellite remote sensing.



Figures from Zhu et al. (2015)

"Tier 1" Geospatial Triggering + Manifestation Models

- We'll use two geospatial models trained on surface manifestation:
  - Zhu et al. (2015) Regional Model (specific to Christchurch, NZ):

$$f(\text{Distance to Rivers, } Vs30\text{, magnitude-scaled } PGA)$$

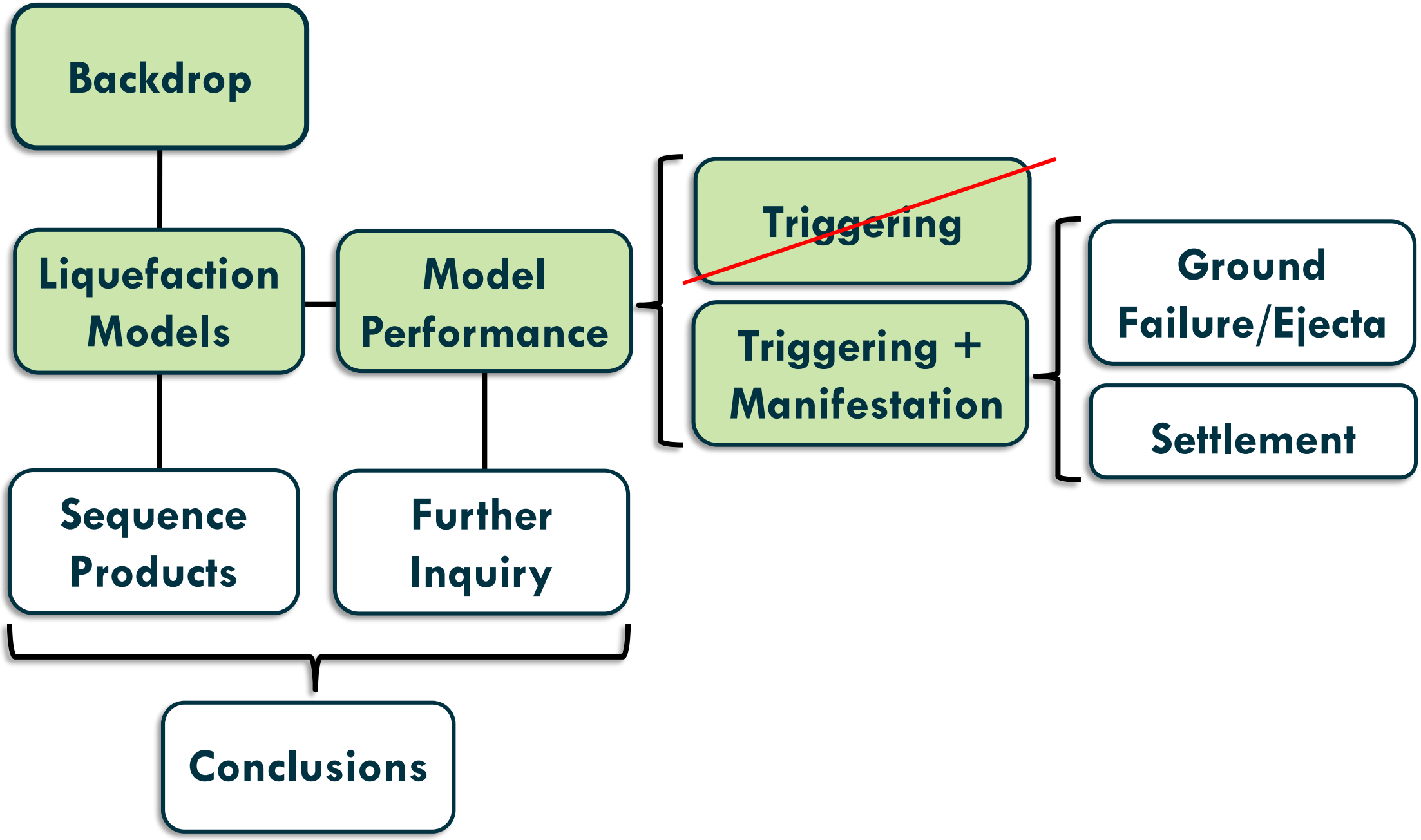
  - Zhu et al. (2017) Global Model (for all other locations):

$$f(\text{Distance to Rivers, Distance to Coast, precipitation, } Vs30\text{, } PGV)$$

Or

$$f(\text{Distance to Water, Water Table Depth, precipitation, } Vs30\text{, } PGV)$$

OUTLINE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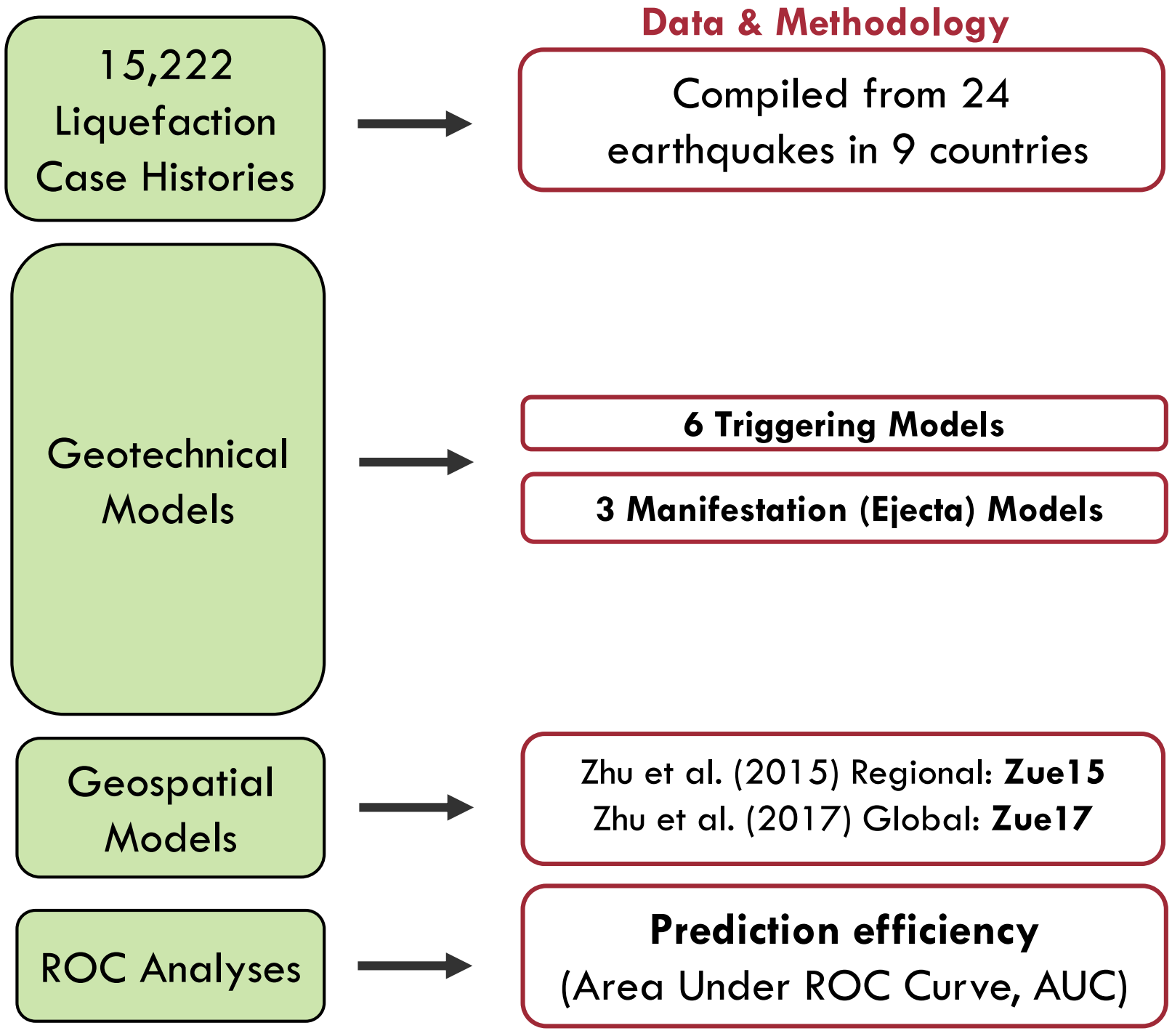
Predicting Ejecta / General Ground Failure



Predicting Ejecta / General Ground Failure

15,222 Liquefaction Case Histories

Geotechnical Models

Geospatial Models

ROC Analyses

No Manifestation

Minor

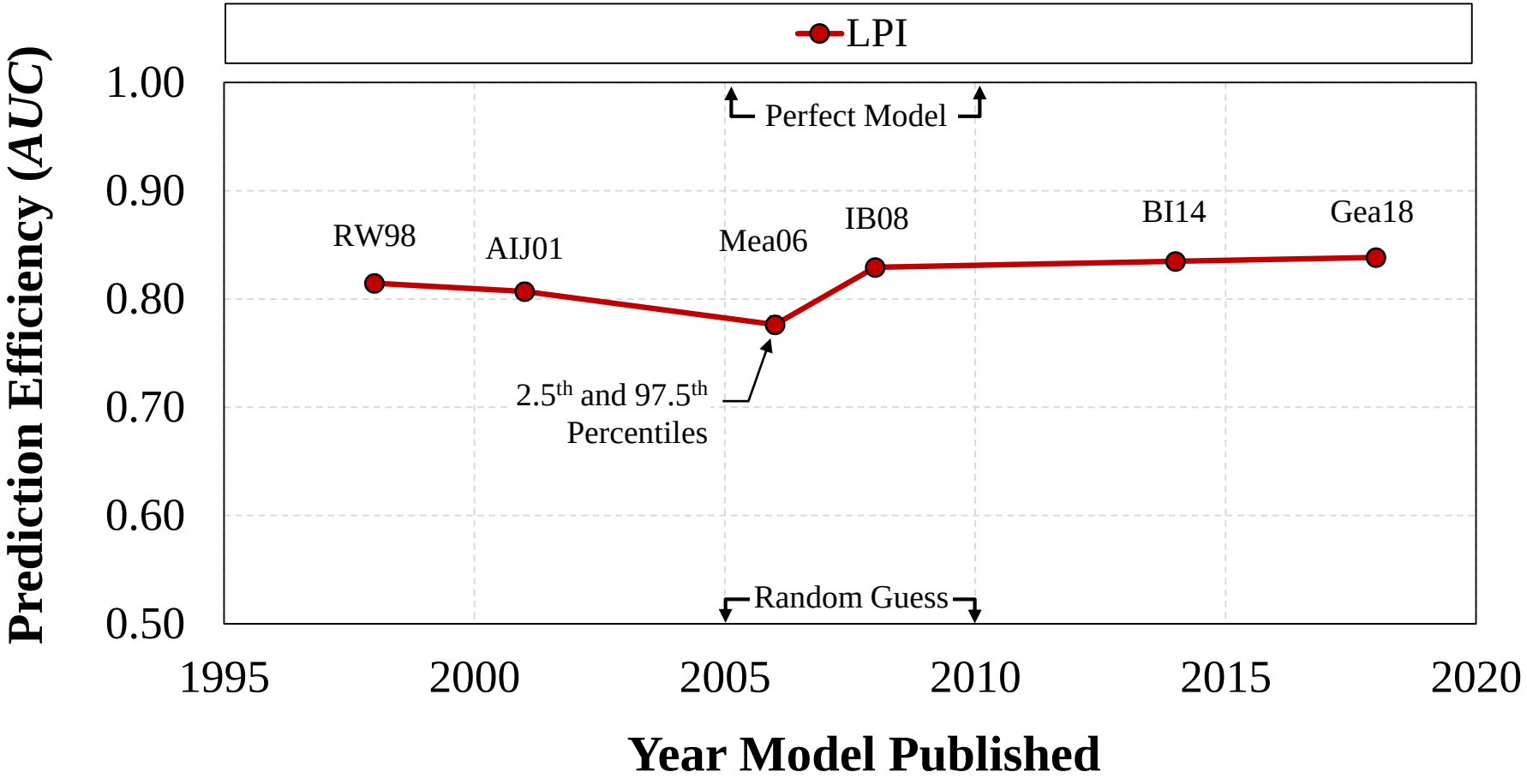
Moderate

Severe

Prediction efficiency
(Area Under ROC Curve, AUC)

Predicting Ejecta / General Ground Failure

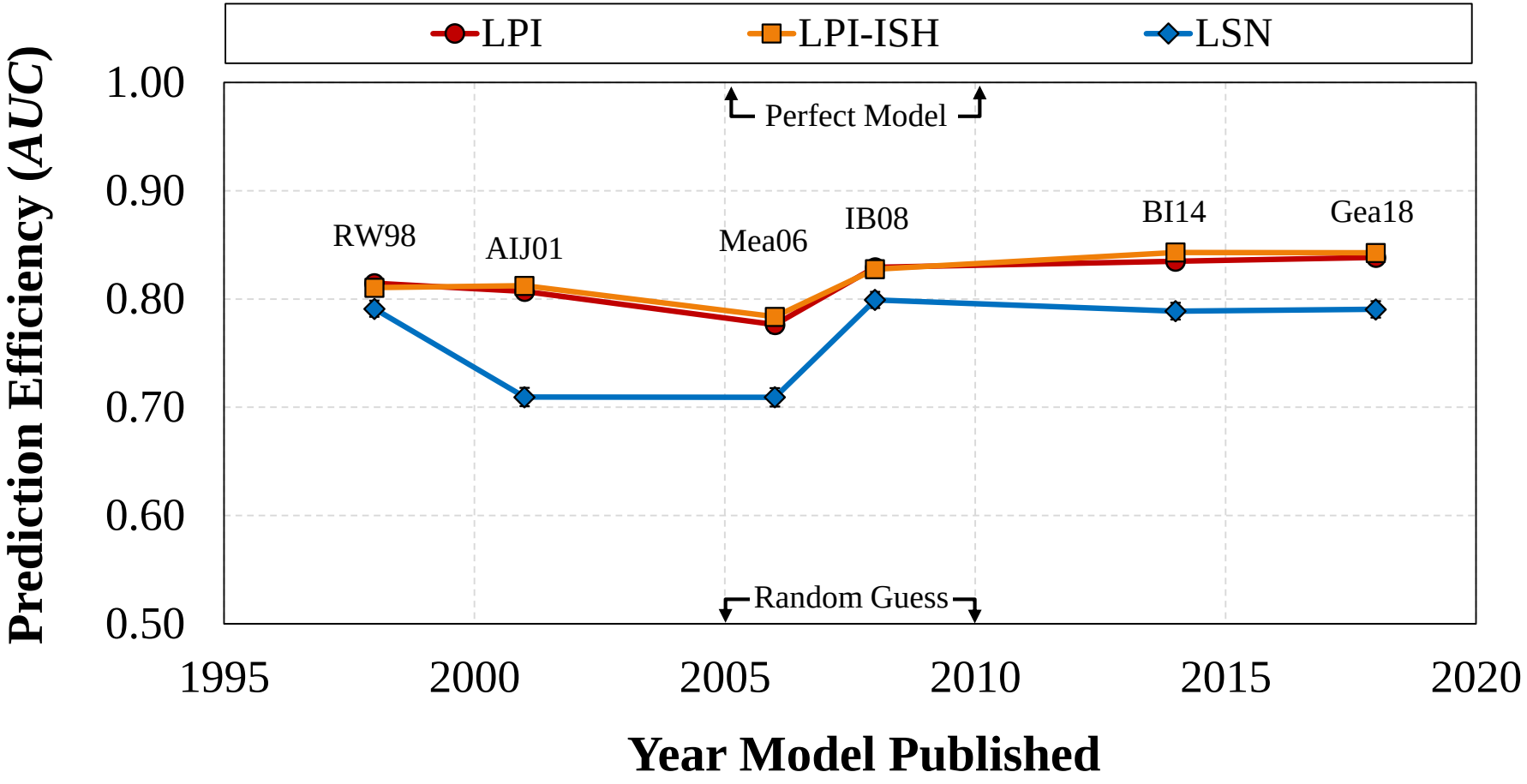
Canterbury Earthquake Sequence
~15000 Case Histories



- Finite-sample uncertainty shown via bootstrap simulations
- Given large data, small differences tend to be statistically significant

Predicting Ejecta / General Ground Failure

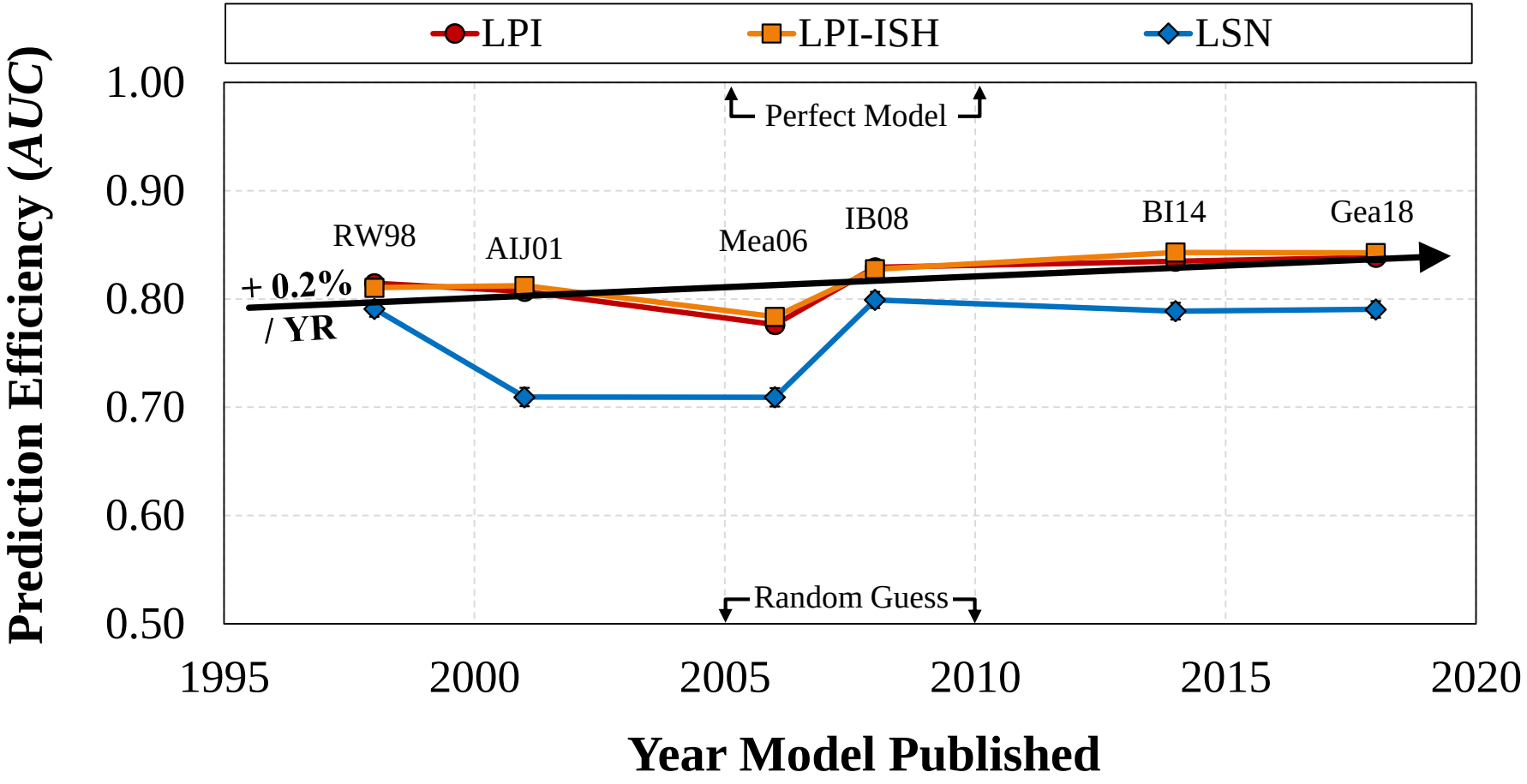
Canterbury Earthquake Sequence
~15000 Case Histories



- **Best models in Canterbury: BI14/LPI$_{ish}$ and Gea18/LPI$_{ish}$**

Predicting Ejecta / General Ground Failure

Canterbury Earthquake Sequence
~15000 Case Histories



Predicting Ejecta / General Ground Failure

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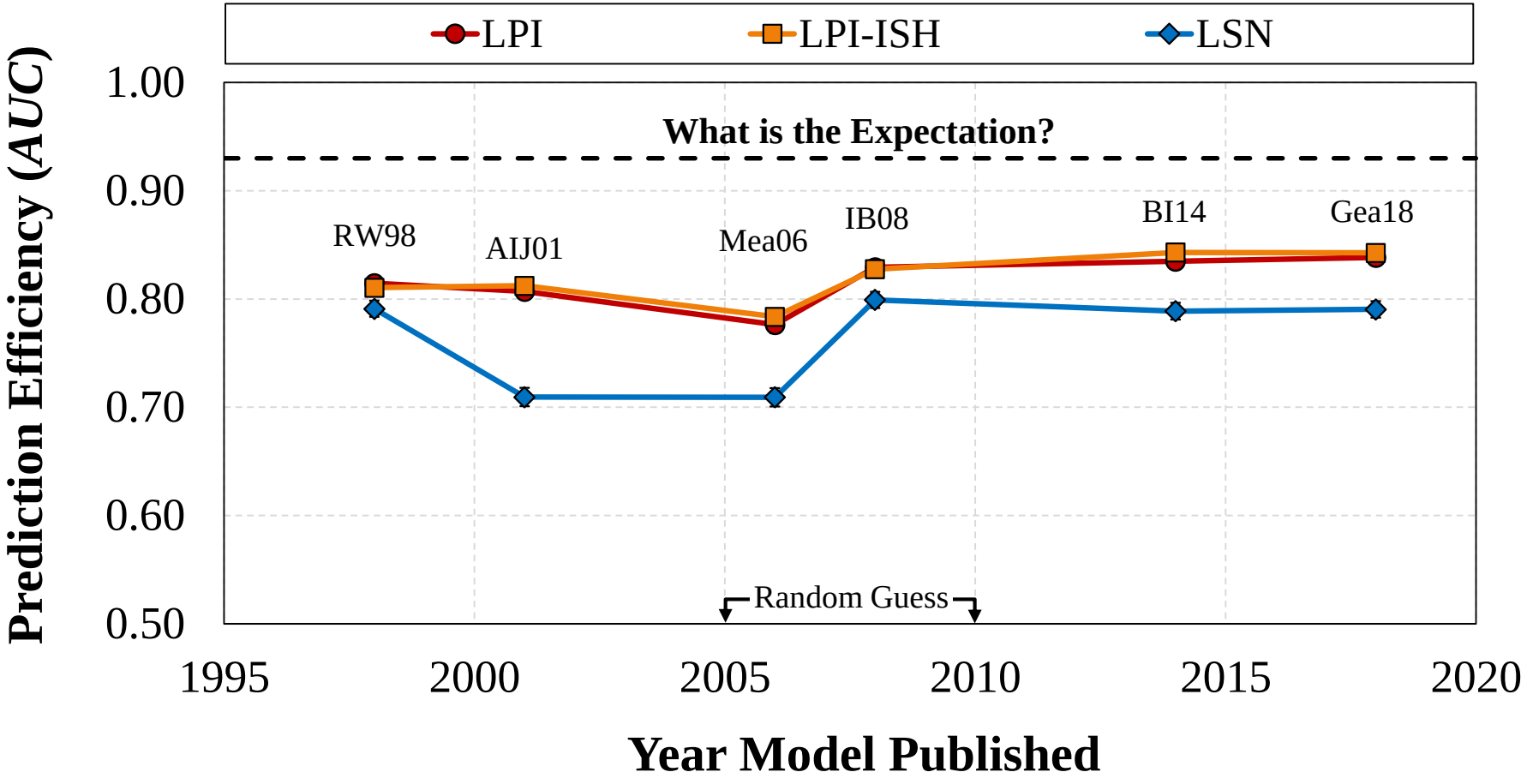
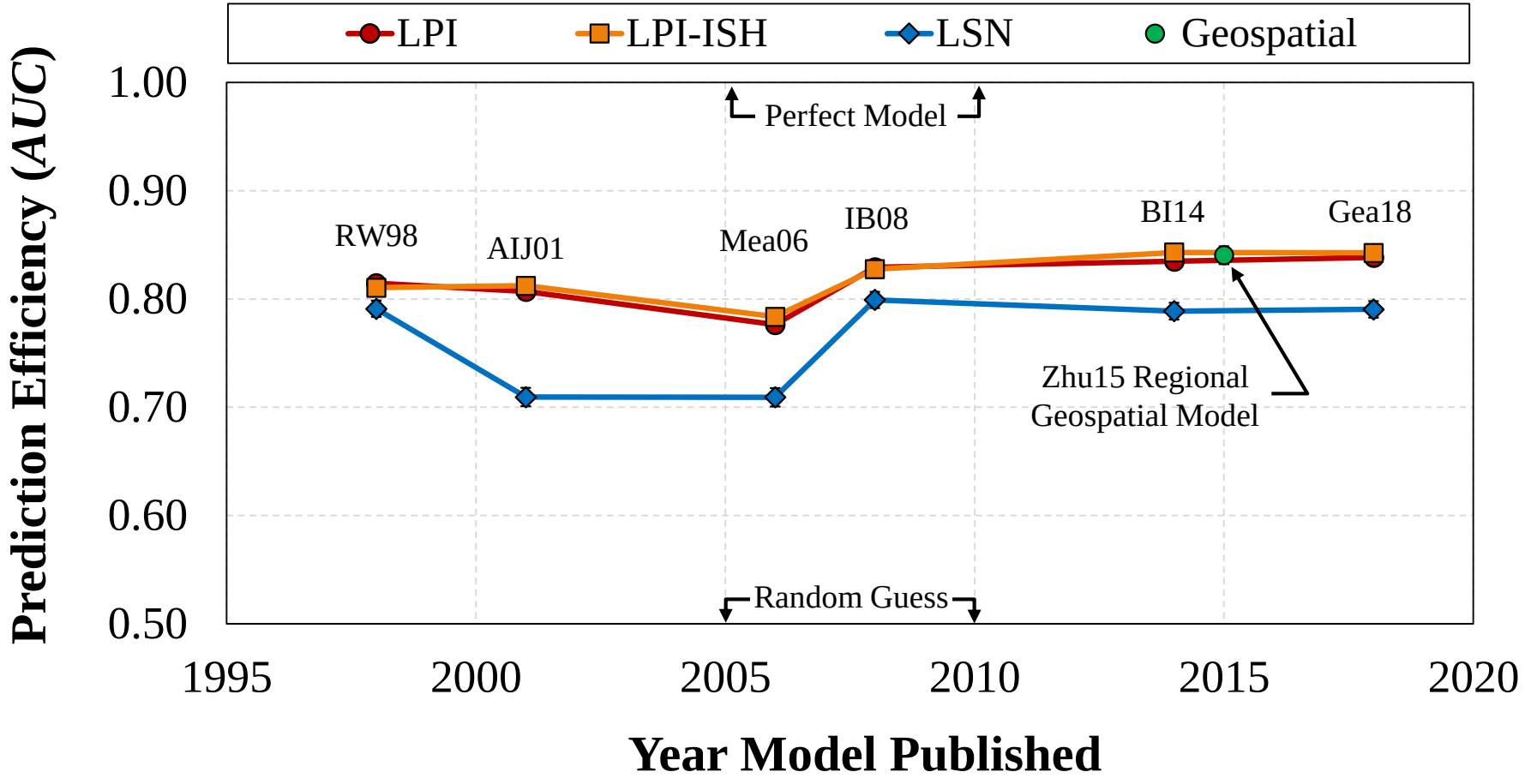


➢ **Most models closer to perfection than to random guessing**

Predicting Ejecta / General Ground Failure

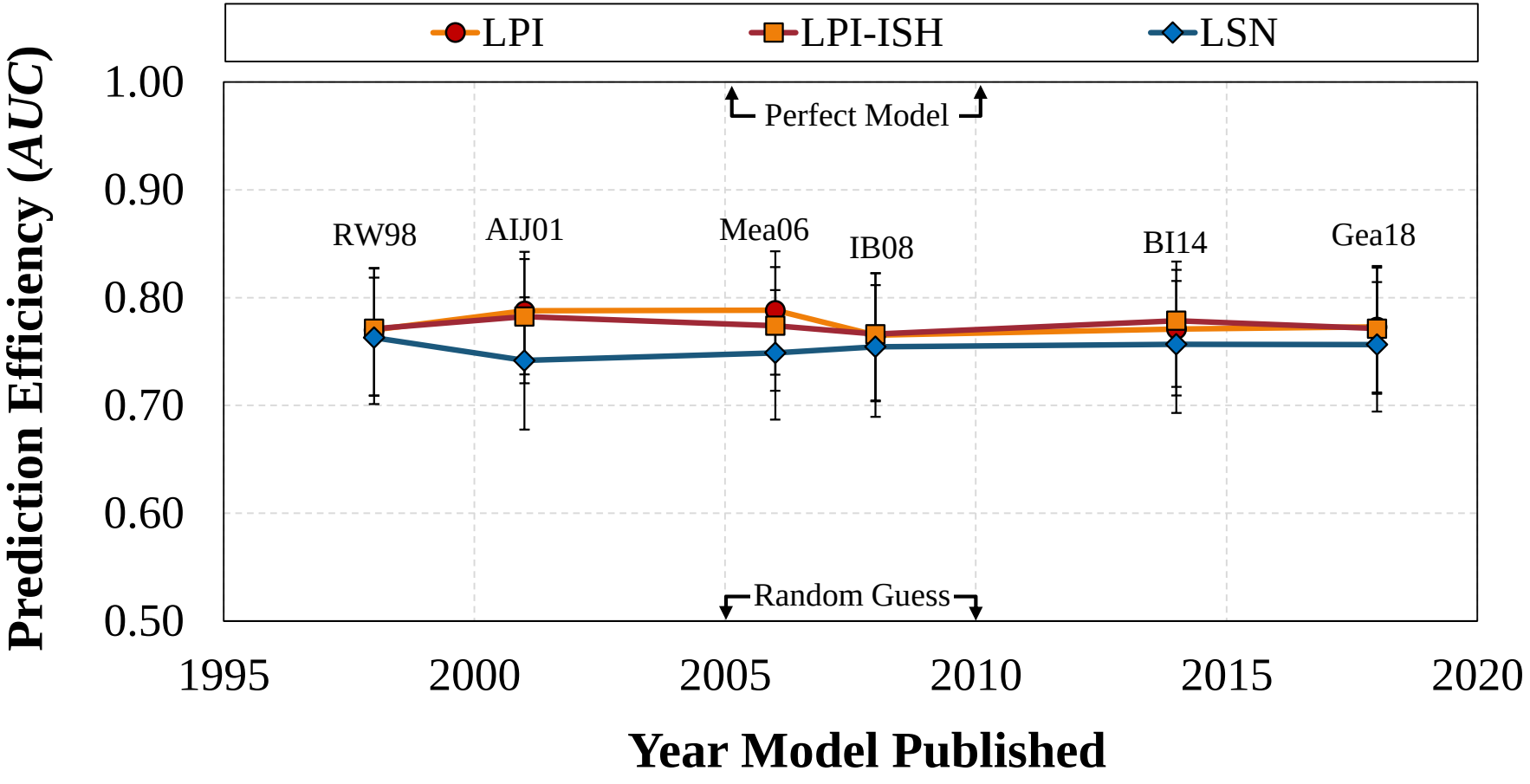
Canterbury Earthquake Sequence
~15000 Case Histories



- **Predictions from outerspace better than in-situ tests?!**

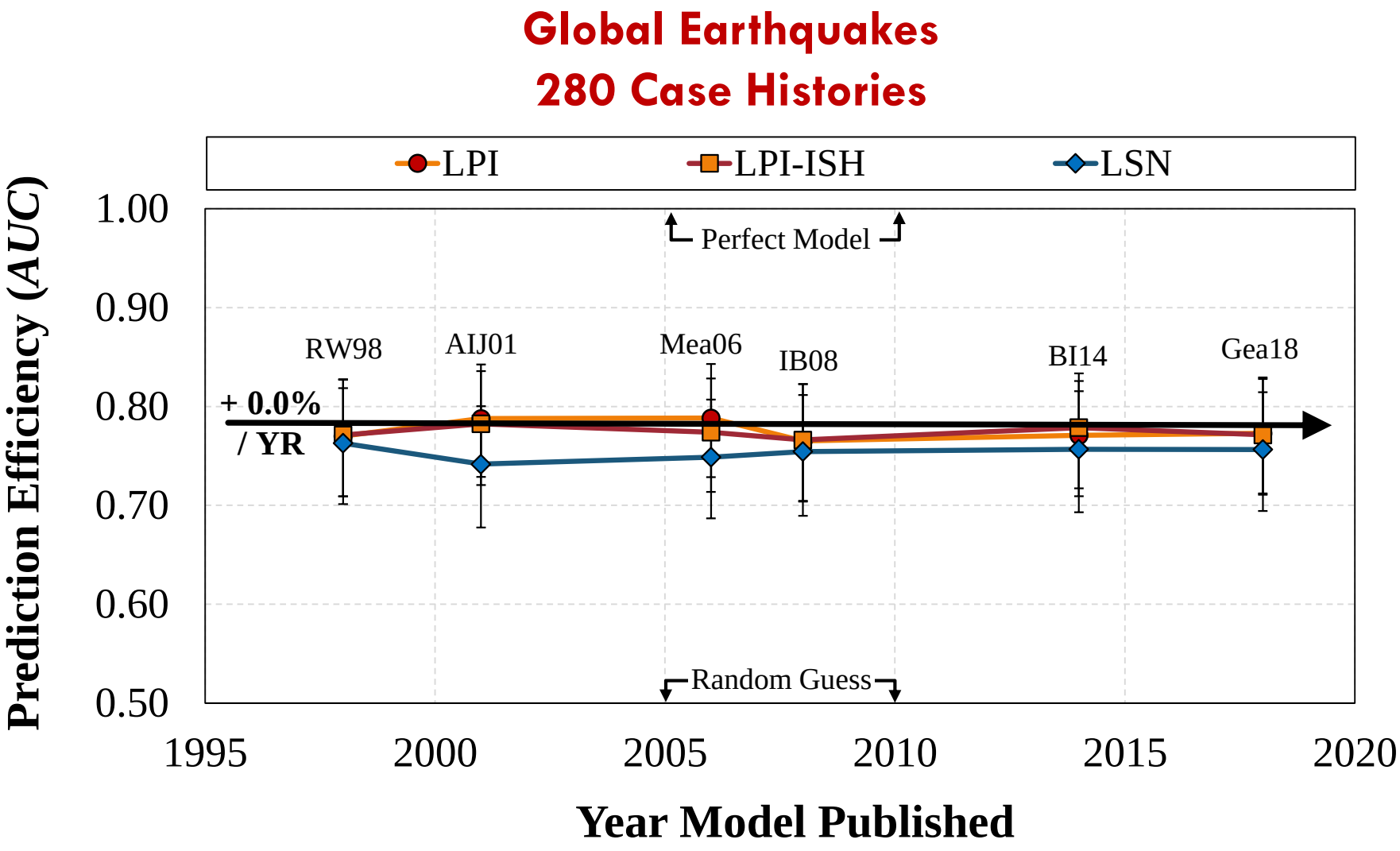
Predicting Ejecta / General Ground Failure

Global Earthquakes
280 Case Histories



- Performance lower, more similar across models
- Best models globally: Mea06/LPI and AIJ01/LPI
- But, model differences are generally not statistically significant

Predicting Ejecta / General Ground Failure



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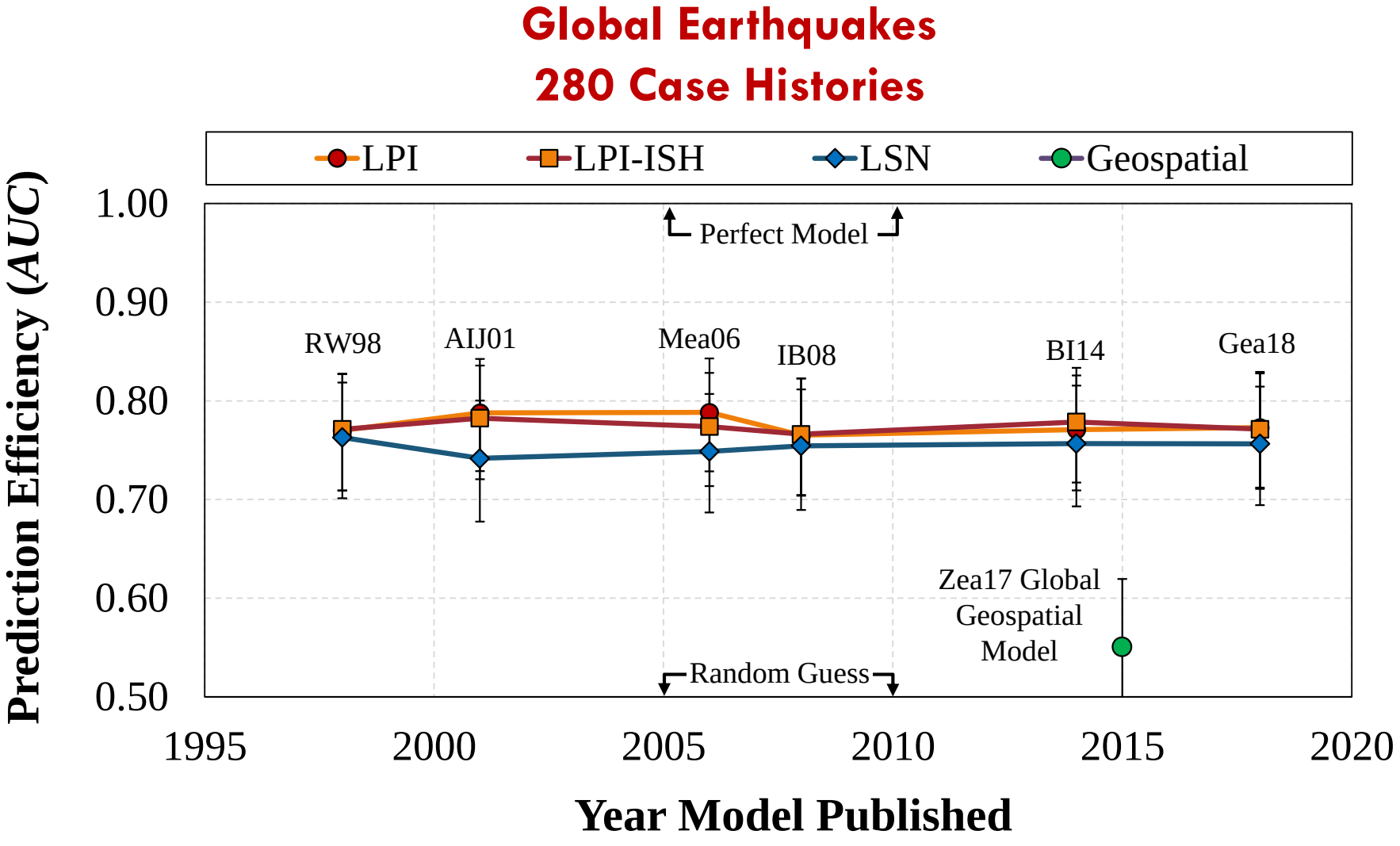
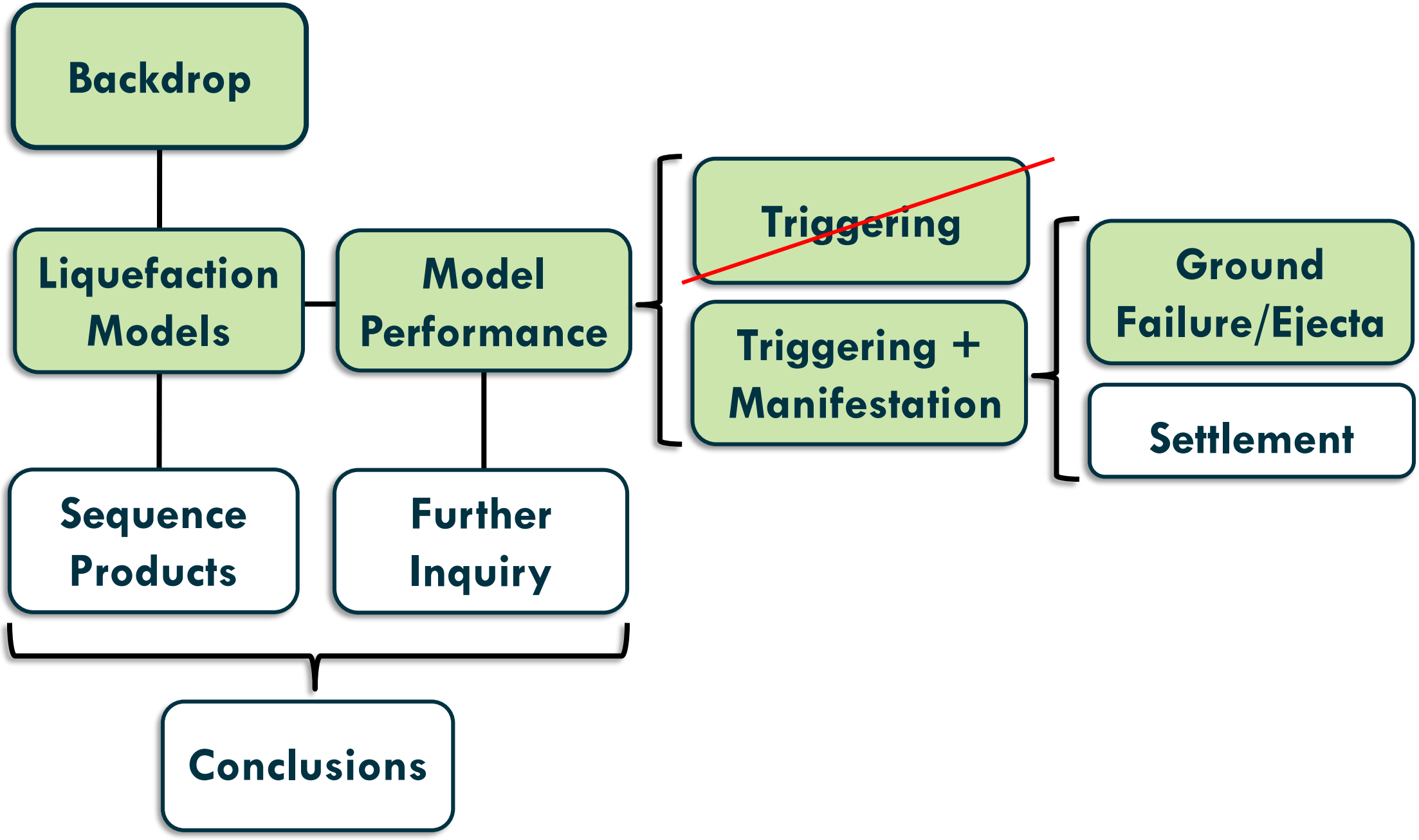


- Globally, geotechnical models much better than geospatial models
- Geospatial models marginally better than random guessing

OUTLINE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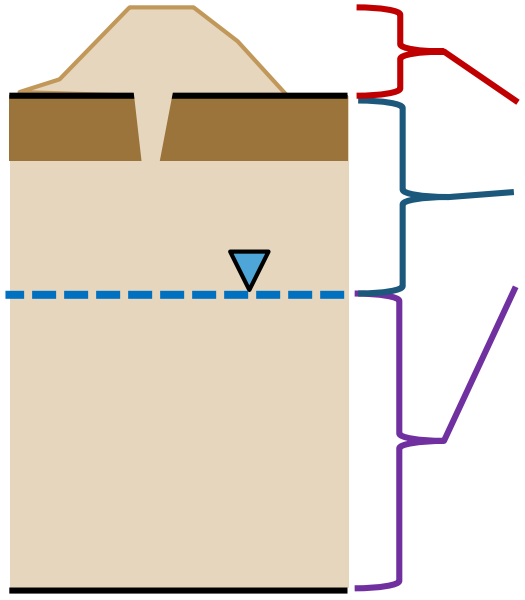
Prediction of Liquefaction-Induced Settlement



Components of Free-Field Settlement

1) Ejecta
2) Seismic Compression
3) Post-Liq volumetric strain, ε_v

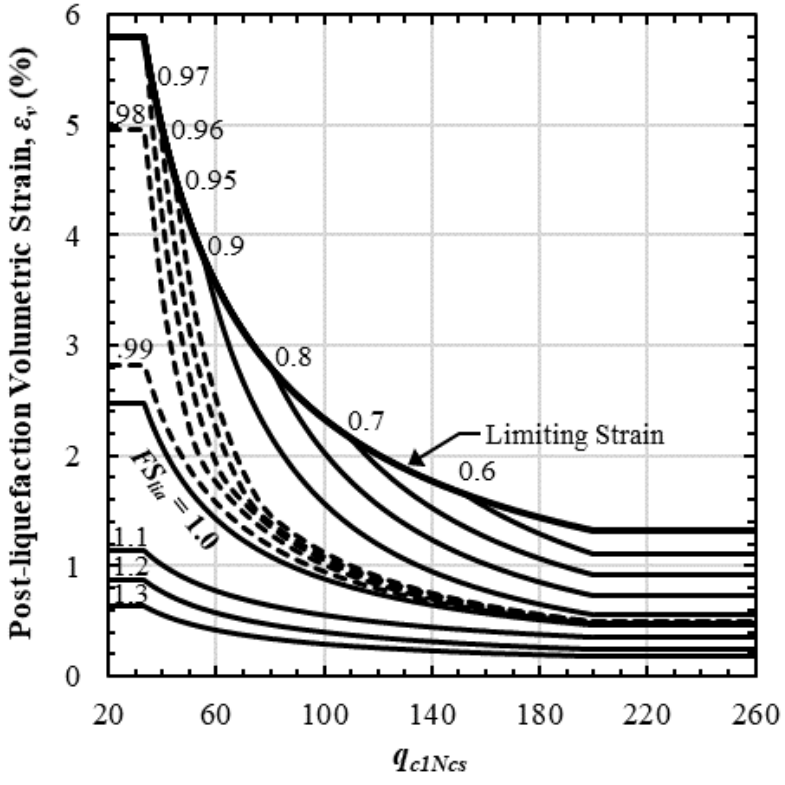
- Most predictions of settlement in practice:
  1) Ignore seismic compression (Unconservative)
  2) Ignore ejecta (Unconservative)
  3) Do not apply depth-weighting to ε_v (Conservative)

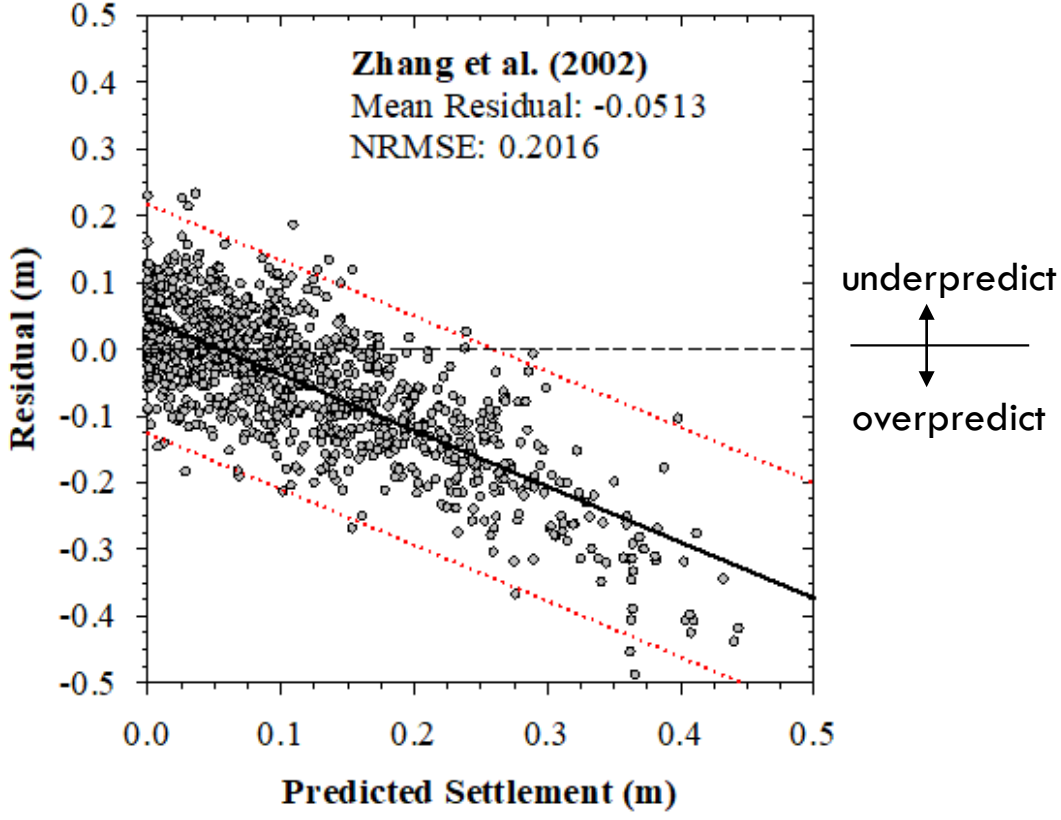
- ε_v often used as "catch-all" predictor of ground settlement
- If prediction is accurate, it is by accident

Prediction of Liquefaction-Induced Settlement

Feb 2011 Christchurch Earthquake (highest quality LIDAR measurement of settlements)

eg, Zhang et al. (2002) with Boulanger & Idriss (2014) triggering model



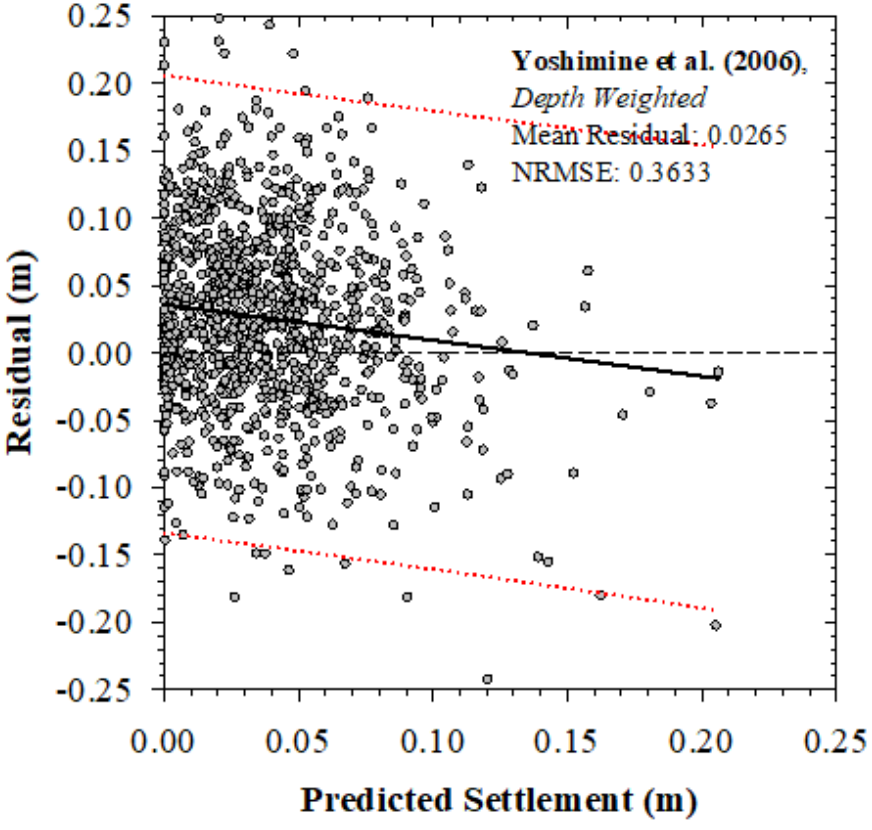


- **Predictions exhibit strong bias**
  - Underpredict small settlement; overpredict large settlement
- True regardless of triggering model and $D_r - q_{c1ncs}$ correlation

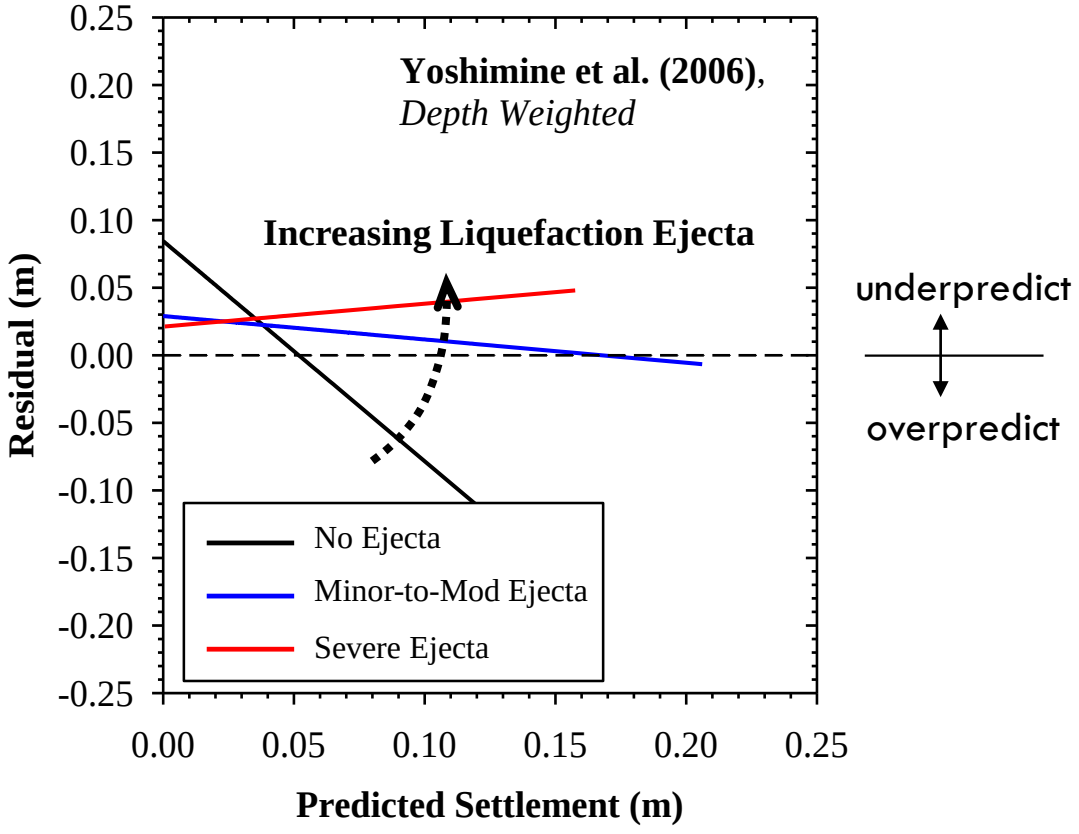
Prediction of Liquefaction-Induced Settlement

Feb 2011 Christchurch Earthquake (highest quality LIDAR measurement of settlements)

With Depth-Weighting Function:



Considering Severity of Ejecta:



- Depth-weighting diminishes prediction bias
- Ejecta clearly needs to be accounted for when predicting settlement
  - Overpredicted at sites w/o ejecta; underpredicted at sites w/ ejecta

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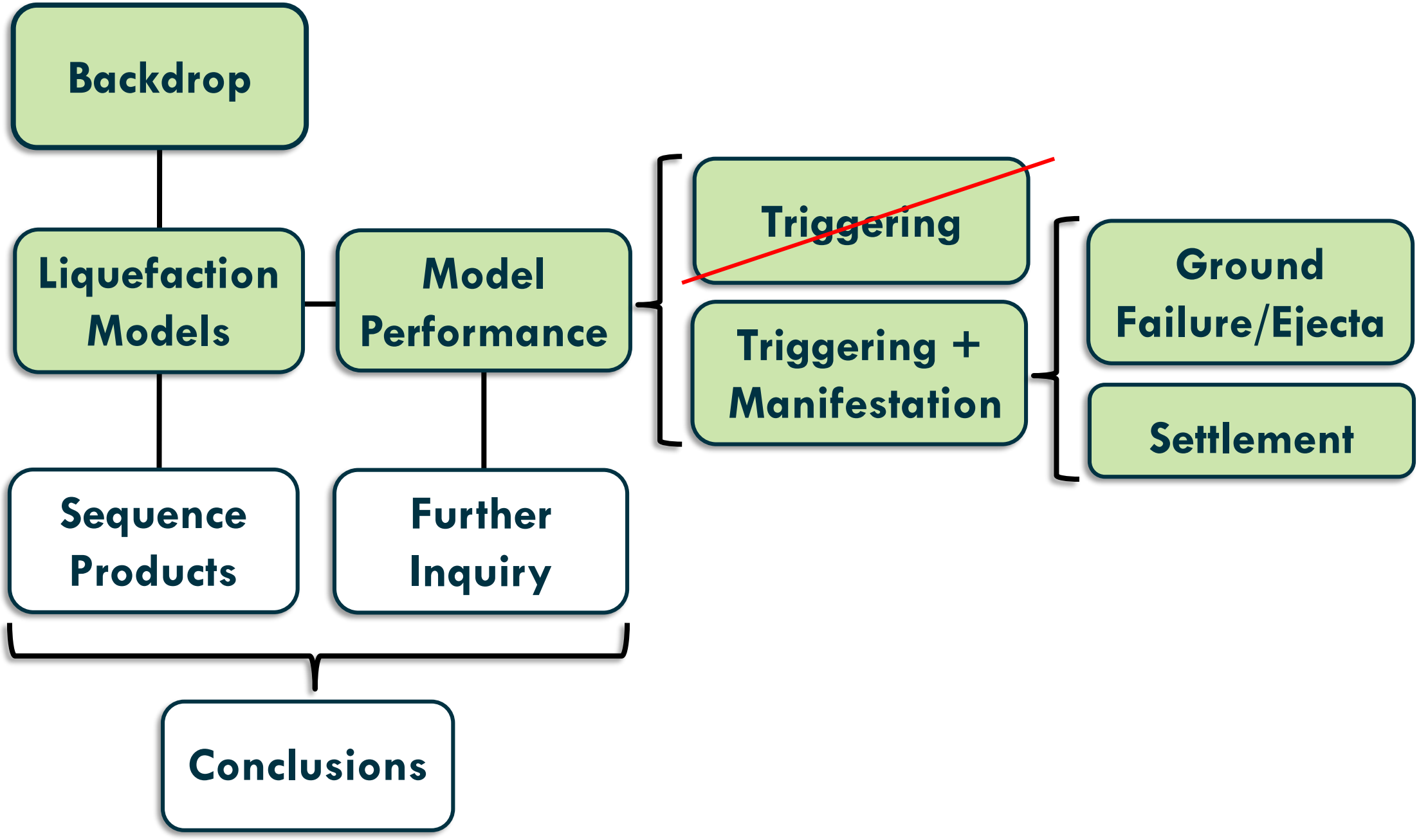
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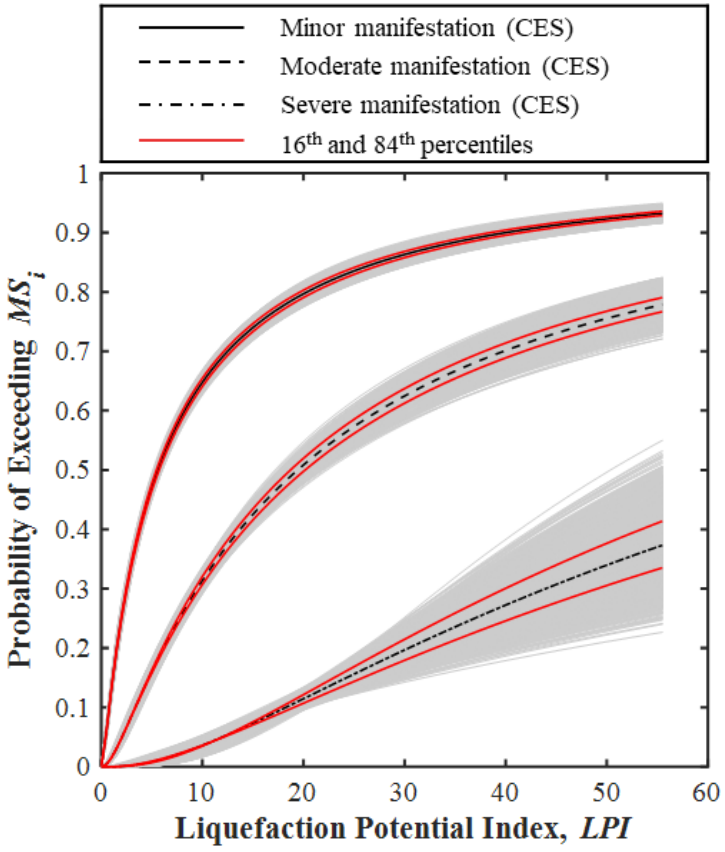
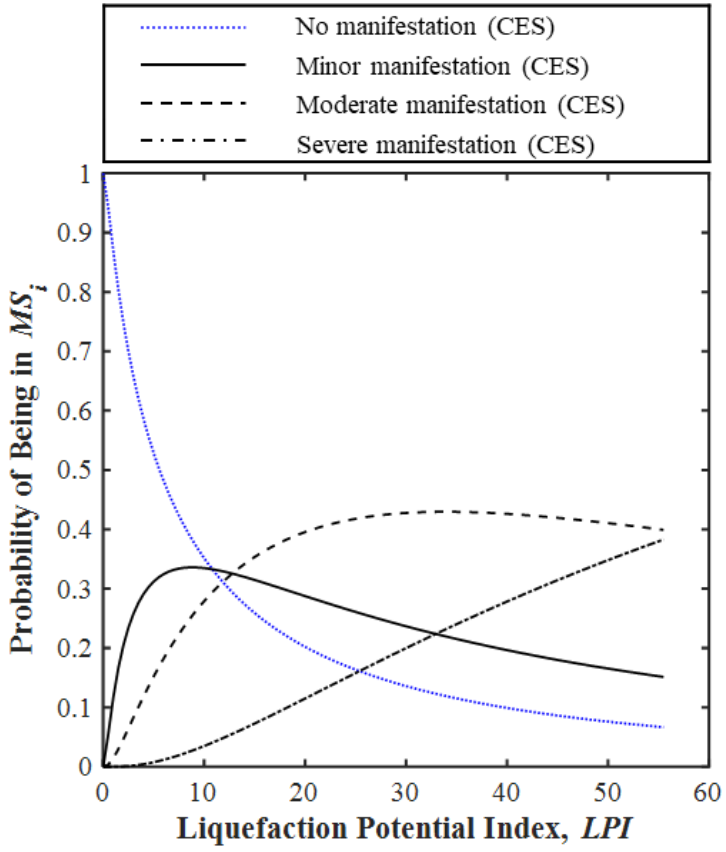
A Few Products of the Canterbury Sequence

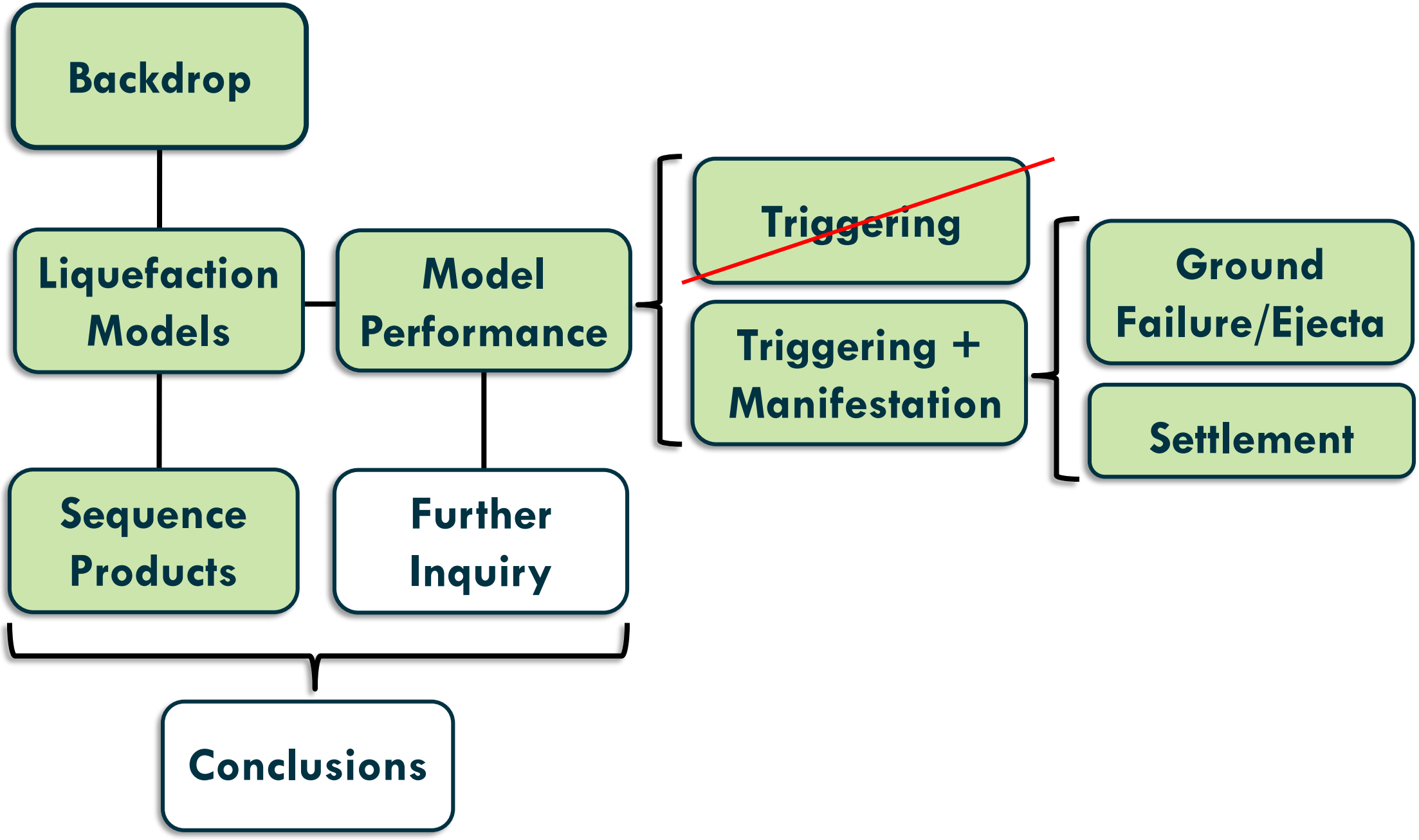
- Fragility Functions for Severity of Free-Field Manifestation (Ejecta)
- Fragility Functions for Severity of Foundation Damage





- Function coefficients for 18 geotechnical models and 2 geospatial models allow user to select analytics of choice (or blend predictions).
- Other new models for predicting foundation settlement and tilt (Bray and Macedo, 2018; Bullock et al., 2019).

OUTLINE


Backdrop
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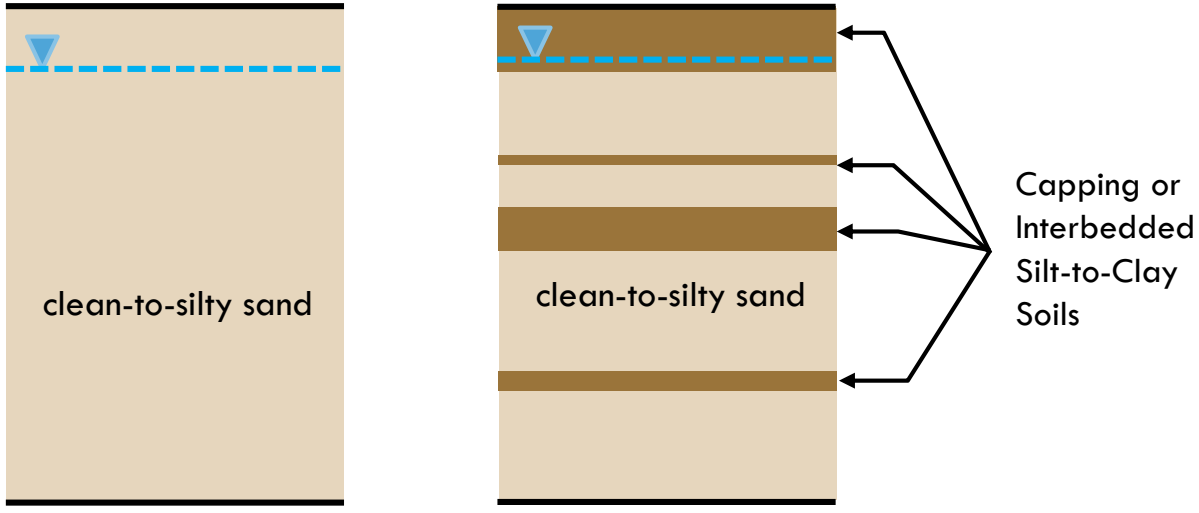
Further Inquiry – Geotechnical Models

- Model performance was particularly poor in Canterbury at sites with interbedded high-I_c soils, where manifestations were overpredicted.



Prediction Efficiency: 80-90% 60-70%

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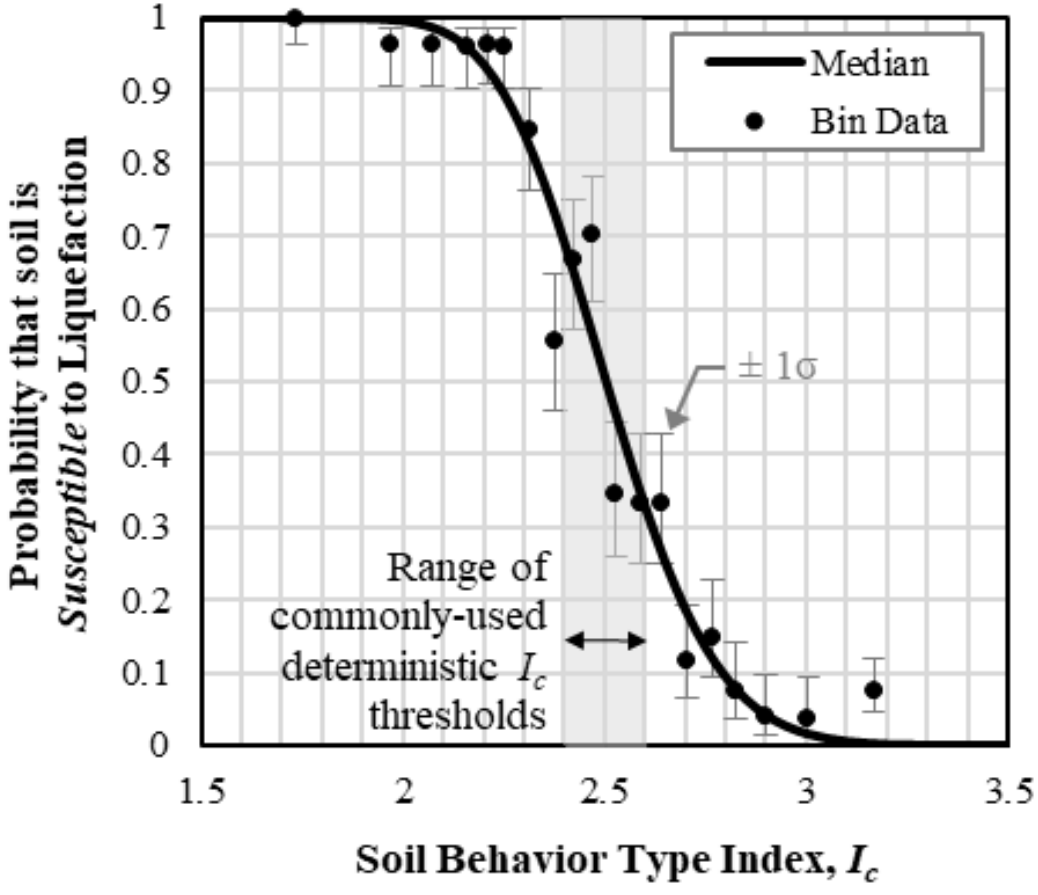
- Problem has something to do with silty soils; what has been investigated?
  1. Region specific I_c-susceptibility correlations (no improvement)



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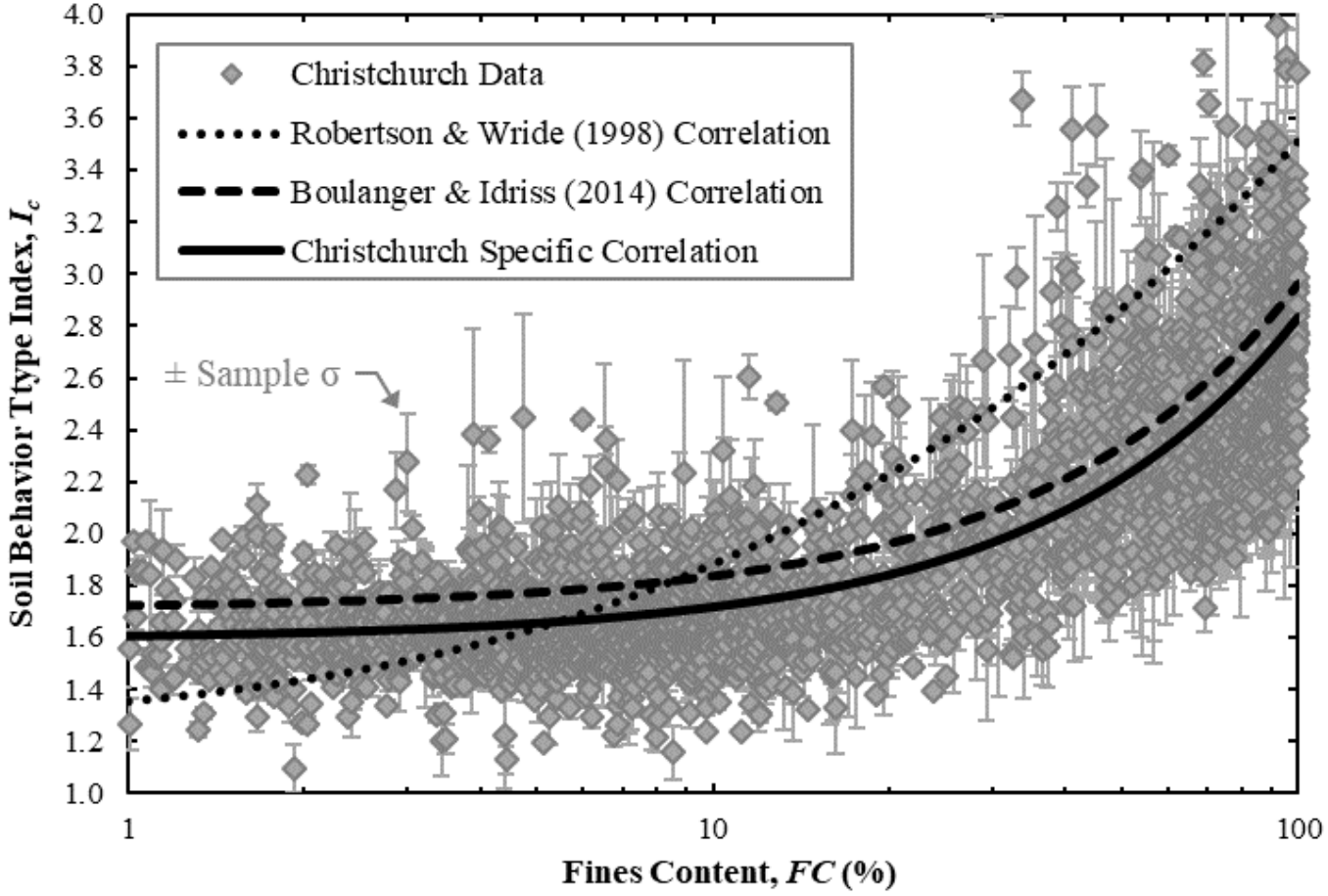

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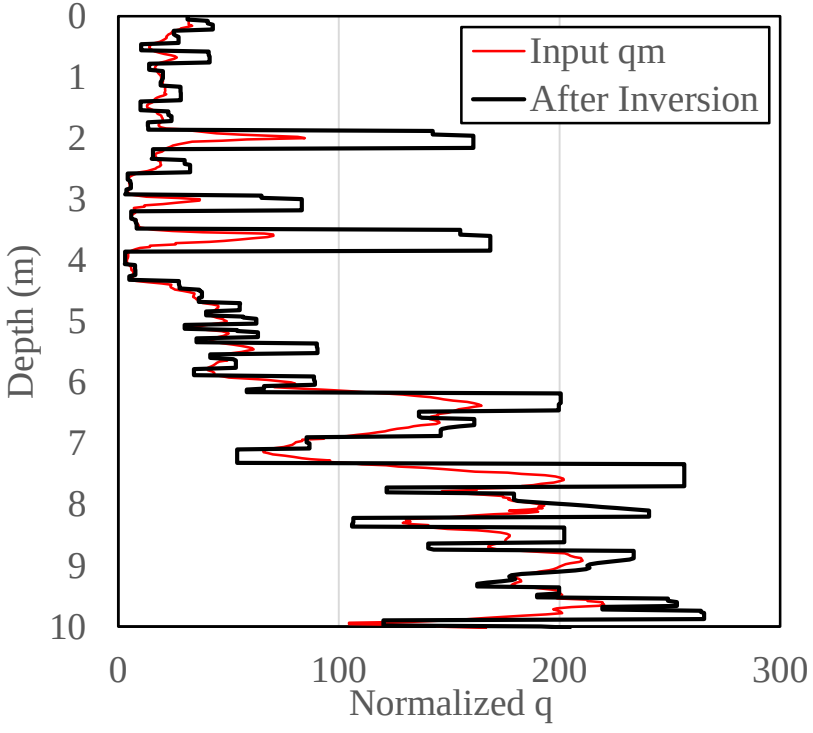

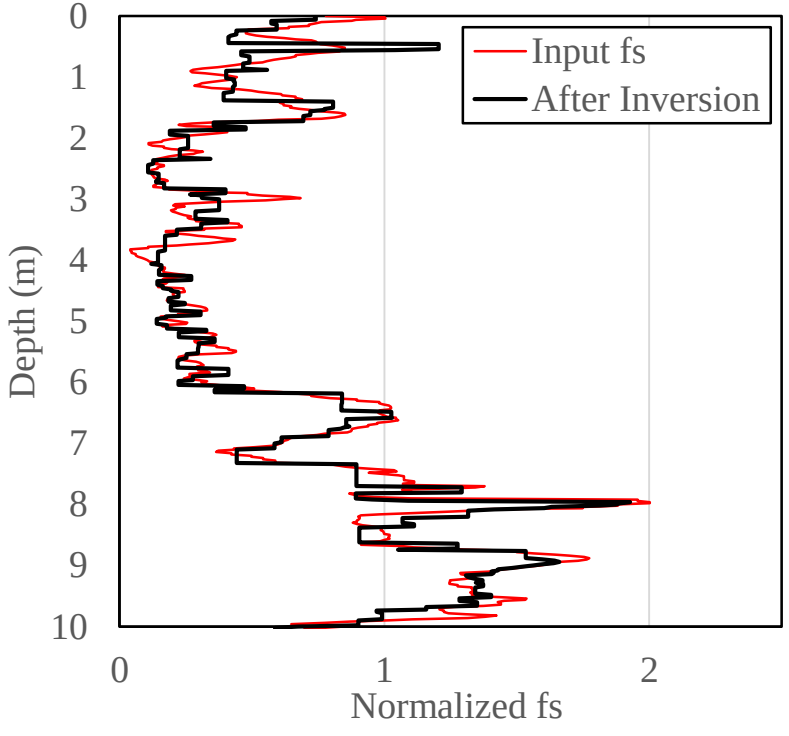

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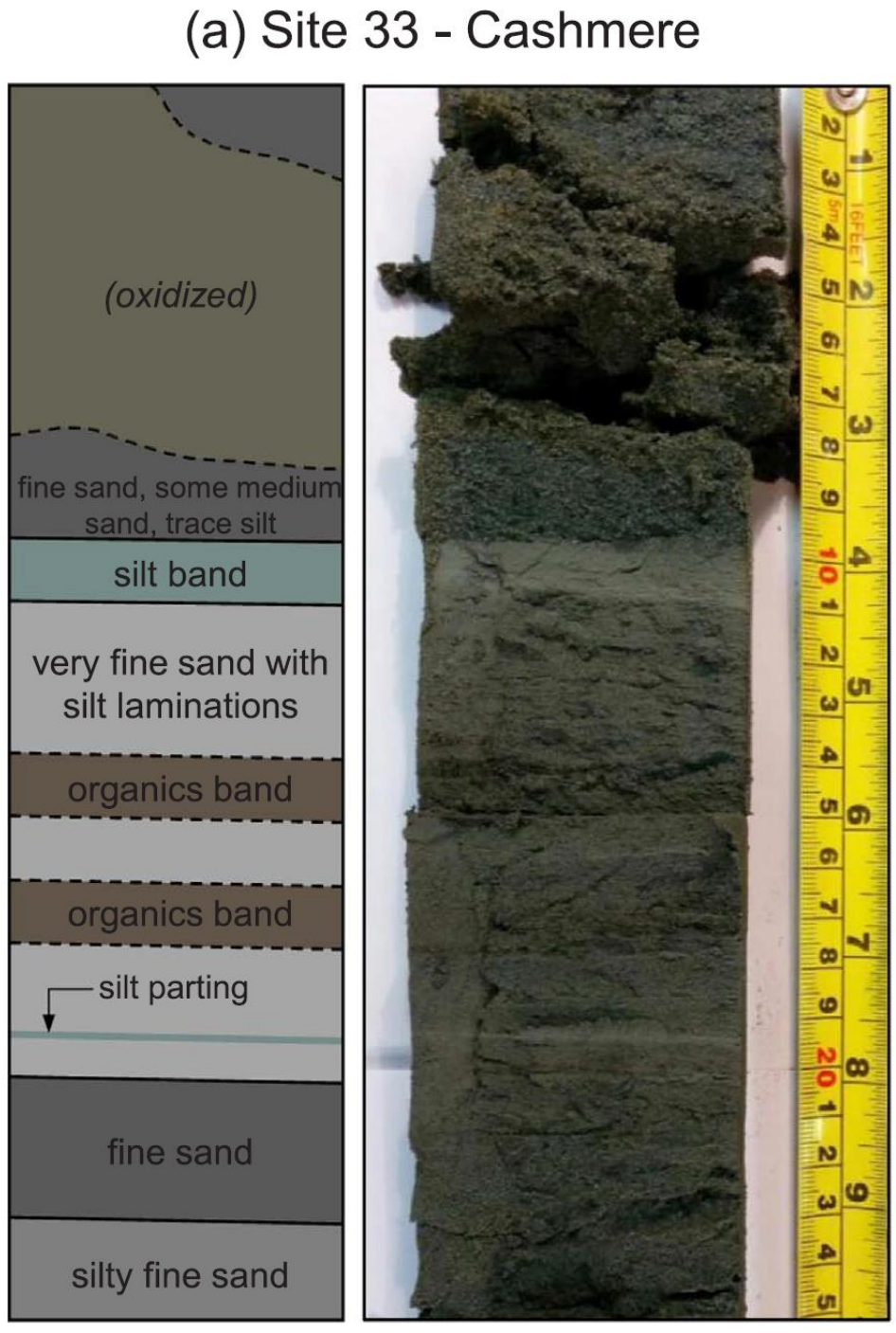
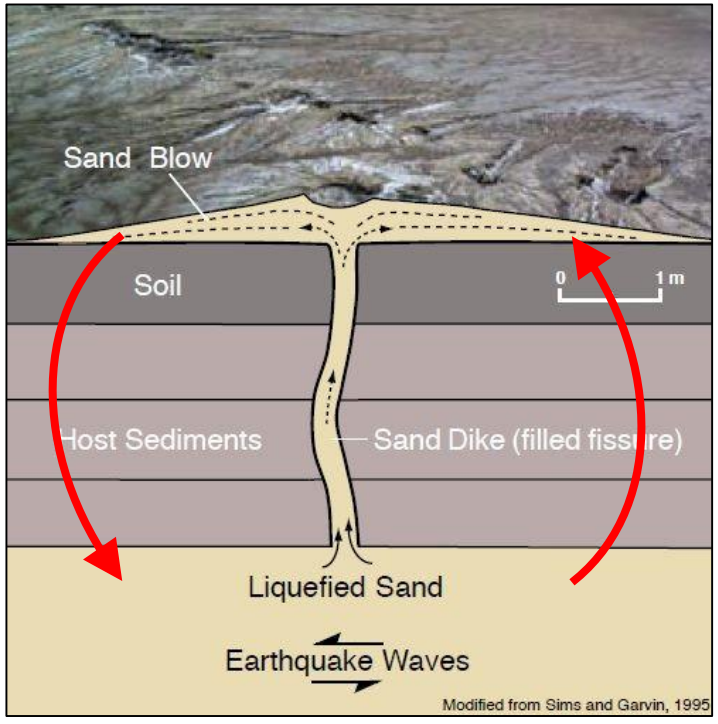
5. Site Characterization Problems
   - Partial Saturation
   - CPT cannot detect very thin layering (Beyzaei et al. 2018). (may help explain poor performance)



Further Inquiry – Geotechnical Models

➢ A final thought on the "simplified" procedure: It could be more rational

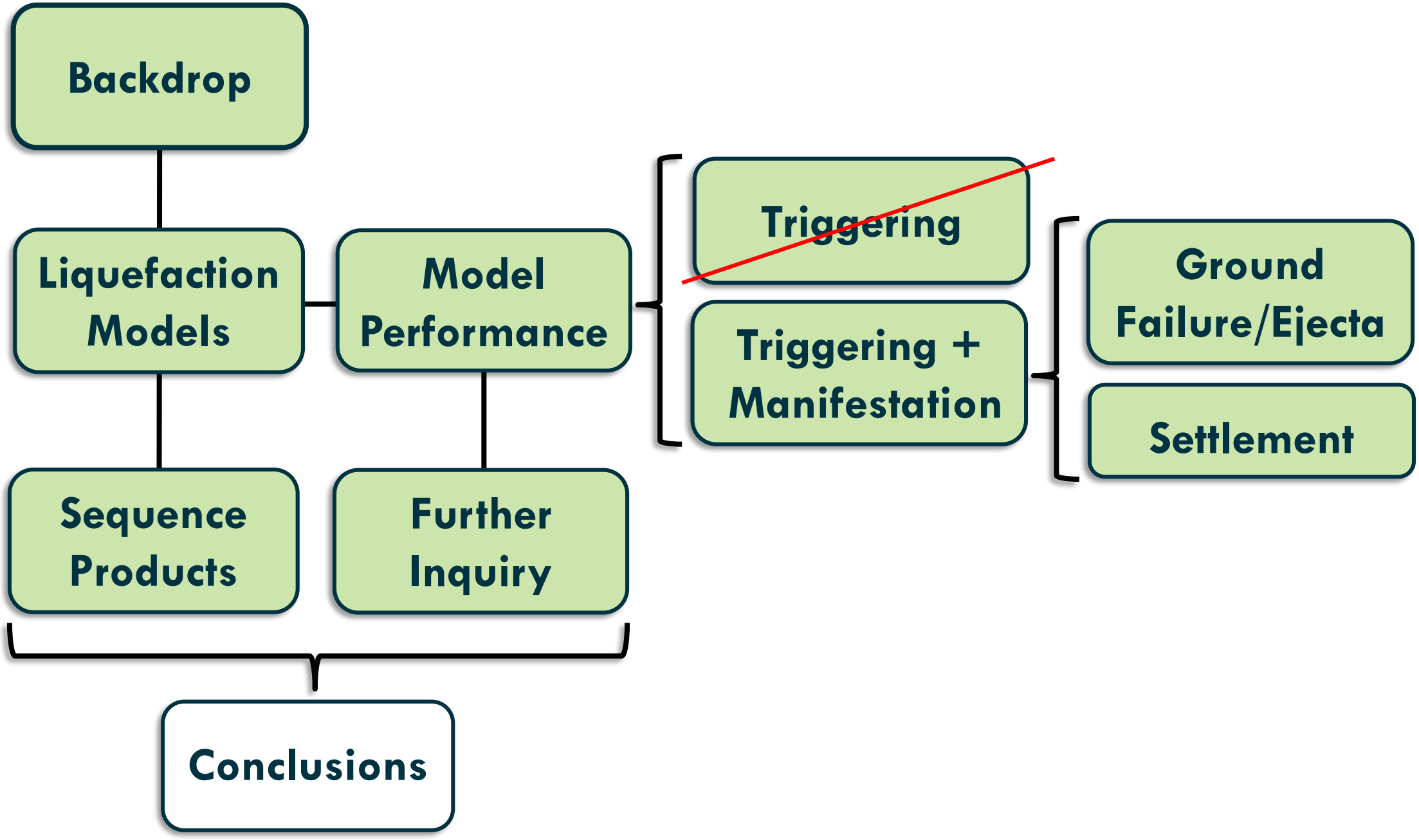
- **Triggering models:** tie surface manifestation to critical layer.
- Need manifestation mechanics to do so.
- Analyst selects critical layer such that thickness, density, strain-potential, and depth, considering also all properties of all overlying soils, is consistent with surface observation.
- Citation of manifestation model: (judgement, year)



- **Manifestation models:** tie triggering to surface manifestation.
- Need manifestation mechanics to do so.
- Names of manifestation models: LPI, LSN, etc.
- Developed separate from triggering models by different researchers, assuming triggering curves are "pure," or devoid of factors relating to manifestation.

➢ Triggering and manifestation models must be developed harmoniously within a consistent framework; current approach (in use for 50 years) fails to do so.

OUTLINE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Conclusions

- Geospatial models outperform geotechnical models for large subsets
  - Global portability is problematic, but potential is provocative
- Geotechnical triggering/settlement models performed poorly in general (if we expect them to be accurate?)
- Geotechnical triggering/ejecta models performed relatively poorly in profiles interbedded with high I_c soils
  - No improvement with region-specific susceptibility correlation
  - No improvement with region-specific I_c-*FC* correlation
  - No improvement with CPT inversion filters (thin layer correction)
  - Impetus for inquiry into site characterization, system response…
  - May highlight very fundamental problem with "simplified" models (obscuration of triggering and manifestation mechanics)

Some Relevant Literature

- Maurer, B.W., Green, R.A., van Ballegooy, S., and Wotherspoon, L. (2019). "Development of region-specific soil behavior type index correlations for evaluating liquefaction hazard in Christchurch, New Zealand." *Soil Dynamics and Earthquake Engineering* 117: 96-105.

- Maurer, B.W., Bradley, B.A., and van Ballegooy, S. (2018). "Liquefaction hazard assessment: satellites vs. in-situ tests." *Geotechnical Earthquake Engineering and Soil Dynamics V: Liquefaction Triggering, Consequences, and Mitigation (S.J. Brandenberg and M.T. Manzari, eds.)*, Geotechnical Special Publication 290: 348-356.

- *Baird, A., Geyin, M., and Maurer, B.W. (2018). "On the relationship between geospatial liquefaction-model performance and quality of geospatial data: a case study of the 2010-2016 Canterbury earthquakes." New Zealand Centre for Earthquake Resilience (QuakeCoRE) Annual Meeting, Sept 4-6; Taupo, New Zealand.*

- *Upadhyaya, S., Maurer, B.W., Green, R.A., and Rodriguez-Marek, A. (2018). "Effect of non-liquefiable high fines-content, high plasticity soils on liquefaction potential index (LPI) performance." Geotechnical Earthquake Engineering and Soil Dynamics V: Liquefaction Triggering, Consequences, and Mitigation (S.J. Brandenberg and M.T. Manzari, eds.), Geotechnical Special Publication 290: 191-198. American Society of Civil Engineers.*

- Maurer, B.W., Green, R.A., Cubrinovski, M., and Bradley, B. (2015). "Assessment of CPT-based methods for liquefaction evaluation in a liquefaction potential index framework." *Géotechnique* 65(5): 328-336.

- Maurer, B.W., Green, R.A., Cubrinovski, M., and Bradley, B. A. (2015). "Fines-content effects on liquefaction hazard evaluation for infrastructure during the 2010-2011 Canterbury, New Zealand earthquake sequence." *Soil Dynamics and Earthquake Engineering* 76: 58-68.

- Maurer, B.W., Green, R.A., Cubrinovski, M., and Bradley, B.A. (2014). "Evaluation of the liquefaction potential index for assessing liquefaction hazard in Christchurch, New Zealand." *Journal of Geotechnical and Geoenvironmental Engineering* 140(7), 04014032, American Society of Civil Engineers.