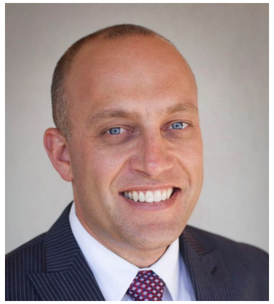
    

NGL Models for Triggering and Manifestation of Liquefaction

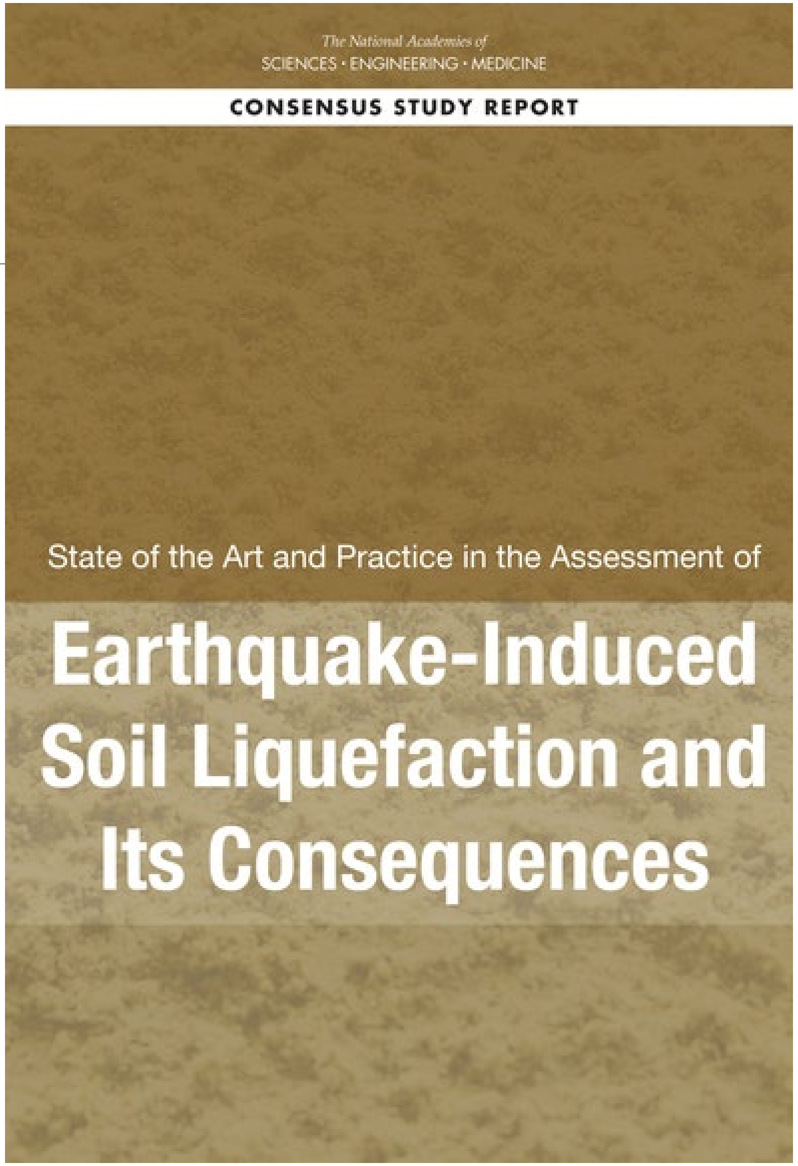
PEER Annual Meeting

Banatao Auditorium, UC Berkeley | March 25, 2025

Kenneth S. Hudson, Kristin Ulmer, Paolo Zimmaro,
Scott J. Brandenberg, Steven L. Kramer, and Jonathan P. Stewart

NGL

Vision


The National Academies of
SCIENCES · ENGINEERING · MEDICINE
CONSENSUS STUDY REPORT
State of the Art and Practice in the Assessment of
Earthquake-Induced Soil Liquefaction and Its Consequences

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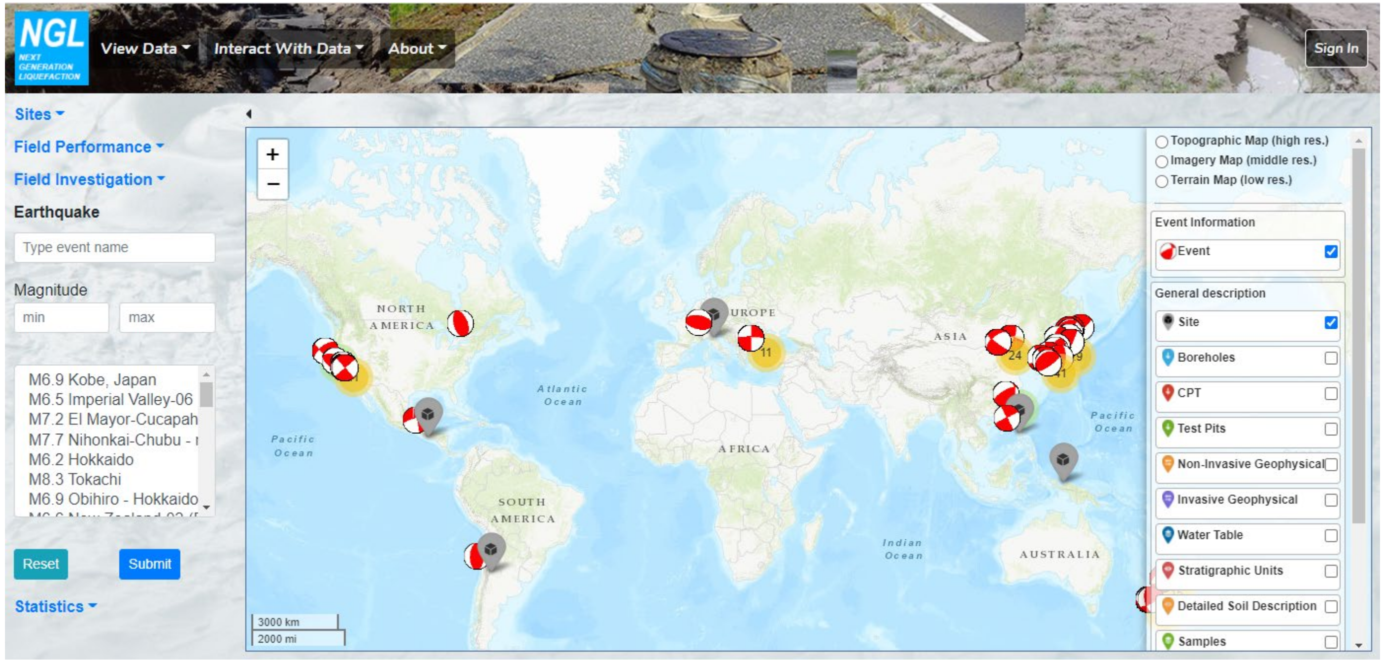
Vision

Database – Supporting Studies – Model Development



https://nextgenerationliquefaction.org/

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Vision

Database – Supp

Model Developm

Community

Joint Management Committee (JMC)
Sponsor Representatives

Project Management Team (PMT)
Kramer, Stamatakos, Stewart

Advisors
Board: Boulanger, Bray, Cubrinovski

Special Advisor: Idriss

Database Working Group (DWG)
Chair: Brandenberg

Focused Studies
Stress effects: Carlton et al.

Susceptibility: Ulmer et al.

Model Development
SMT: Kramer, Brandenberg, Hudson, Ulmer, Zimmaro

CU Boulder: Dashti, Kamai, Liel et al.

DOT Pooled Fund: Olson, Rollins, Stuedlein et al.

NGI: Carlton, Geyin et al.

Turkey-US: Cetin, Moss, Kayen et al.

UW/Tufts: Baise, Maurer, Thompson

VT: Green, Rodriguez-Marek, Stafford

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Modeling: General approach

NGL project provides unique opportunities relative to prior work:

Data: more case histories, more information per case history, efficient utilization

Fully probabilistic: models account for and characterize epistemic uncertainty and aleatory variability

Ground motions: derived in a consistent manner to their evaluation in forward analyses (PSHA) for new and legacy events

Profile behavior: accounts for “system effects” on profile response (e.g. Cubrinovski et al. 2019)

Terminology & Philosophy

Susceptibility: potential of soil to experience significant pore pressure generation and strength loss; evaluated as a fundamental material characteristic.

Triggering: occurs in liquefaction-susceptible soils when the liquefaction demand exceeds capacity; produces high pore pressures and temporary strength loss.

Manifestation: surface evidence of liquefaction triggering (e.g., sediment ejecta, instabilities).

Observed field performance = manifestation (or lack thereof) – should be distinguished from triggering

Outline

Bayesian approach

Triggering “prior” P(T|S)

Manifestation models derived from case histories

Updated P(T|S) model

Outline

Bayesian approach

Triggering “prior” P(T|S)

Manifestation models derived from case histories

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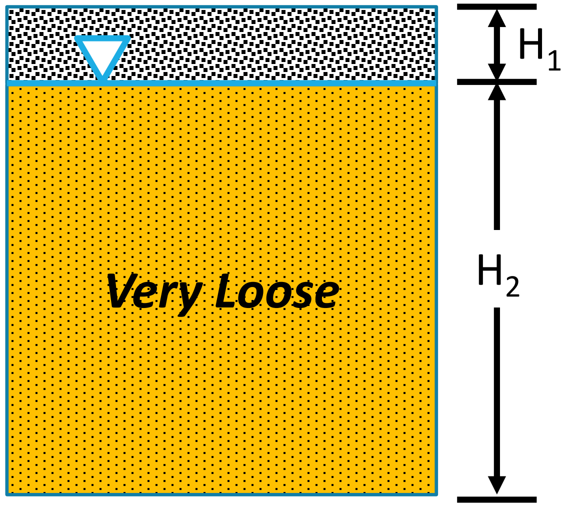
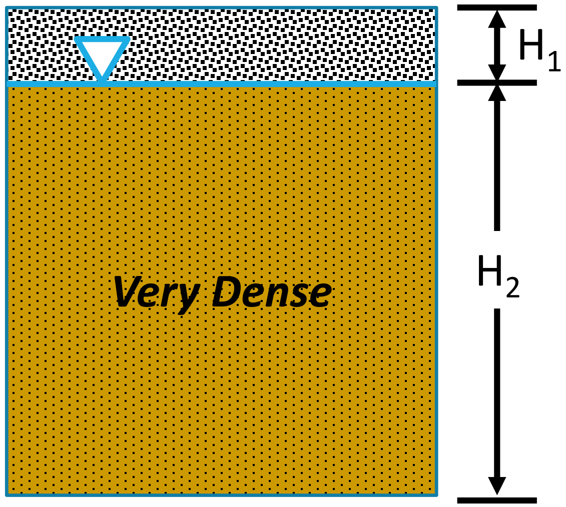
Triggering and Manifestation

1) Manifestation observed



2) Manifestation ***not*** observed



Thin crust, thick susceptible layer

P[T] very high

P[M|T] very high

P[M] = P[M|T] P[T] very high

Thin crust, thick susceptible layer

P[T] very low

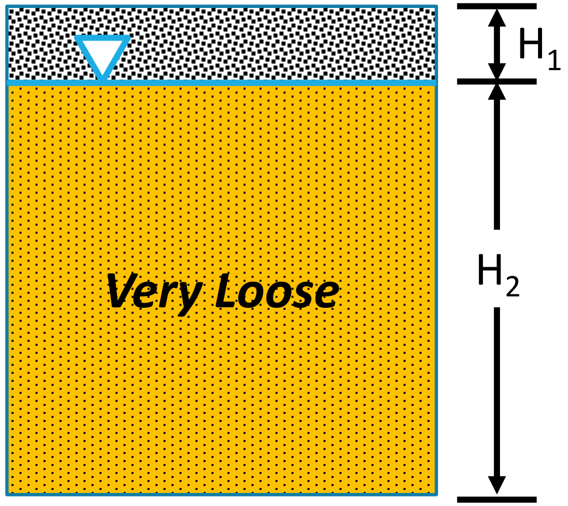
P[M|T] high

P[M] = P[M|T] P[T] very low

P[NM] = 1 – P[M] very high

Triggering and Manifestation

1) Manifestation observed



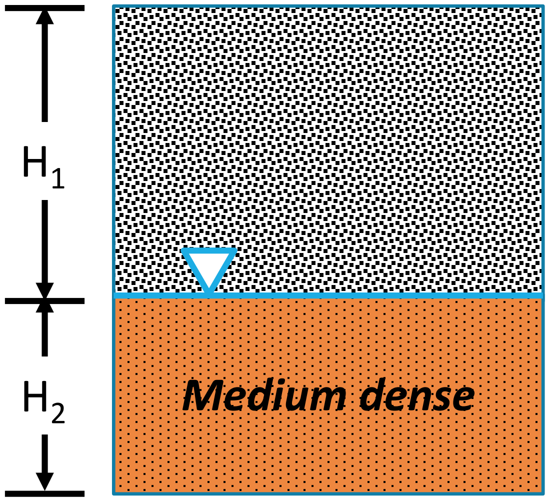
Thin crust, thick susceptible layer

P[*T*] very high

P[*M*|*T*] very high

P[*M*] = P[*M*|*T*] P[*T*] very high

3) Manifestation ***not*** observed



No manifestation – why not?

Because soil was too dense to trigger?

Because manifestation was inhibited?

Intermediate crust, Intermediate susceptible layer

P[*T*] intermediate

P[*M*|*T*] intermediate

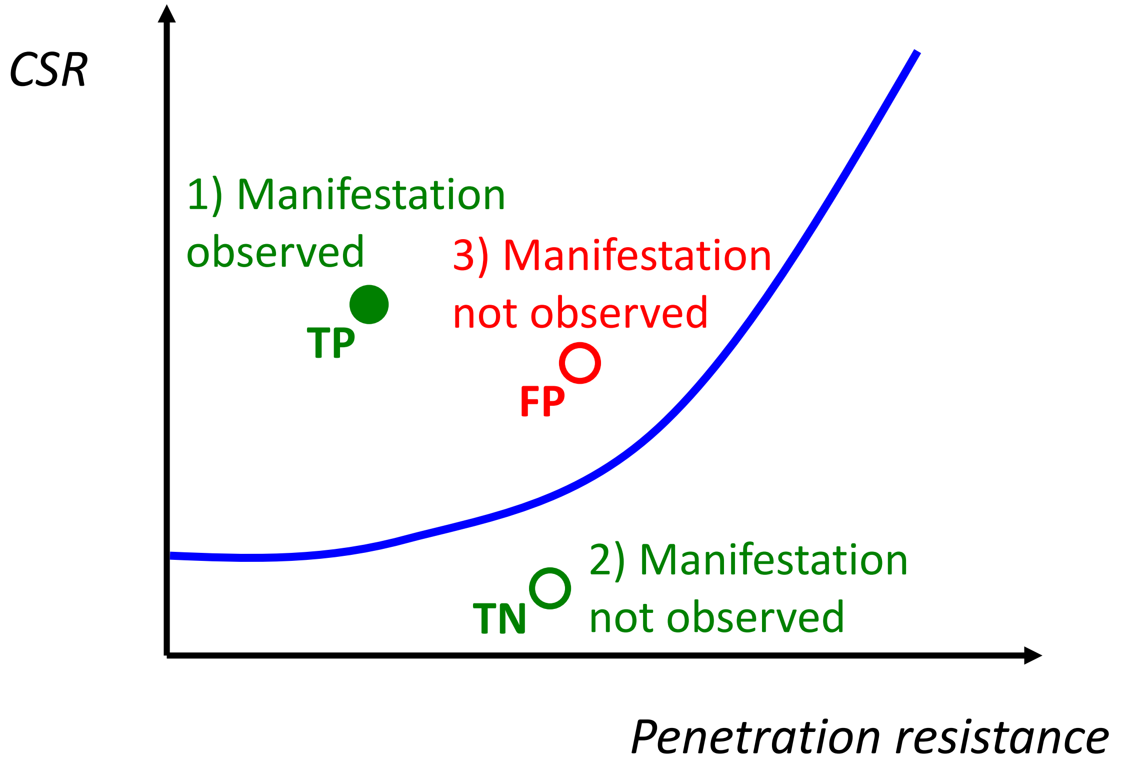
P[*M*] = P[*M*|*T*] P[*T*] intermediate

Triggering and Manifestation

Legacy models represent profile with a critical layer

Case histories plot as a point in CSR-PR space

Boundary curve typically interpreted as triggering "strength"



Probabilistic Approach: Required Elements

Bayes theorem:

$$P[T \mid M] = \frac{P[M \mid T]P[T]}{P[M]}$$

Need three probabilities:

- Probability of manifestation given triggering, $P[M|T]$
- Probability of manifestation without triggering, $P[M|NT]$

$\left.\begin{array}{l} P[M|T] \\ P[M|NT] \end{array}\right\}$ Probabilistic manifestation models

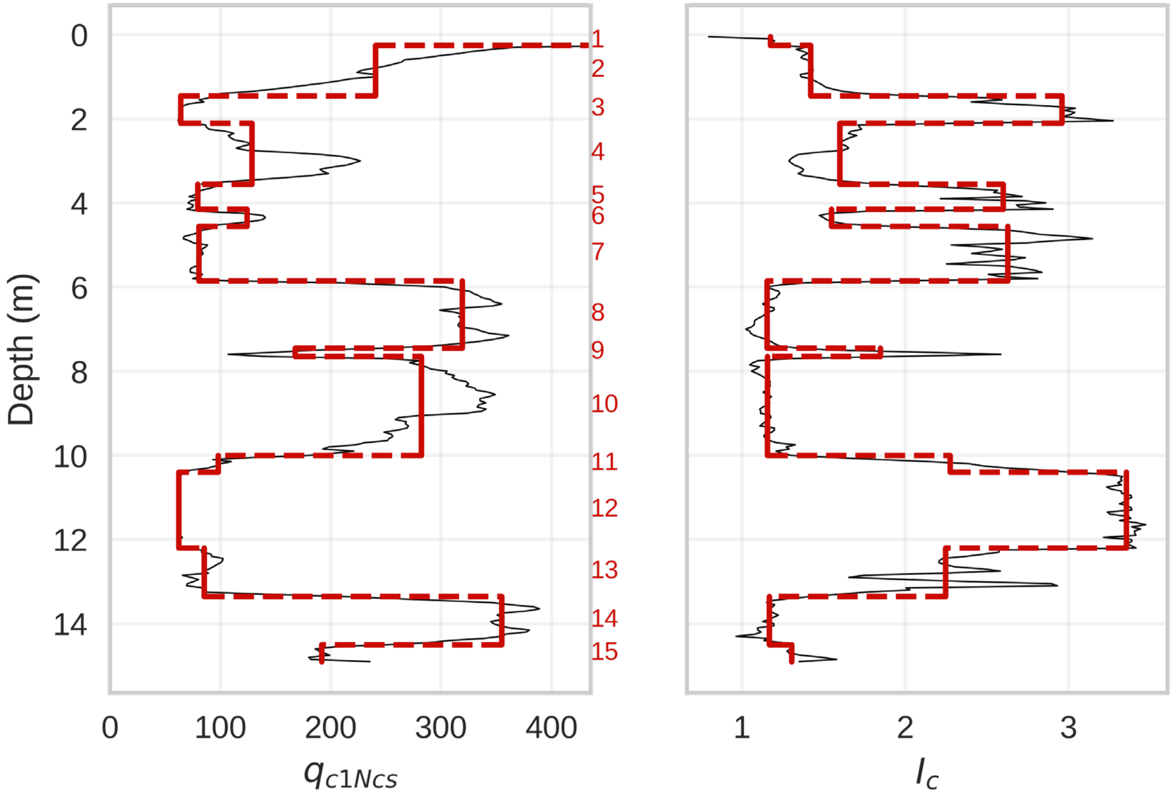
- Probability of triggering before seeing this data, $P[T]$ - prior probability

Profile based approach

Automated discretization of CPT profiles (available at ngl_tools)

Susceptibility and triggering evaluated layer-by-layer

Surface manifestation model derived using profile



Hudson et al. (2023)

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Modelling approach

Bayesian approach

Triggering “prior” P(T|S)

Manifestation models derived from case histories

Updated P(T|S) model

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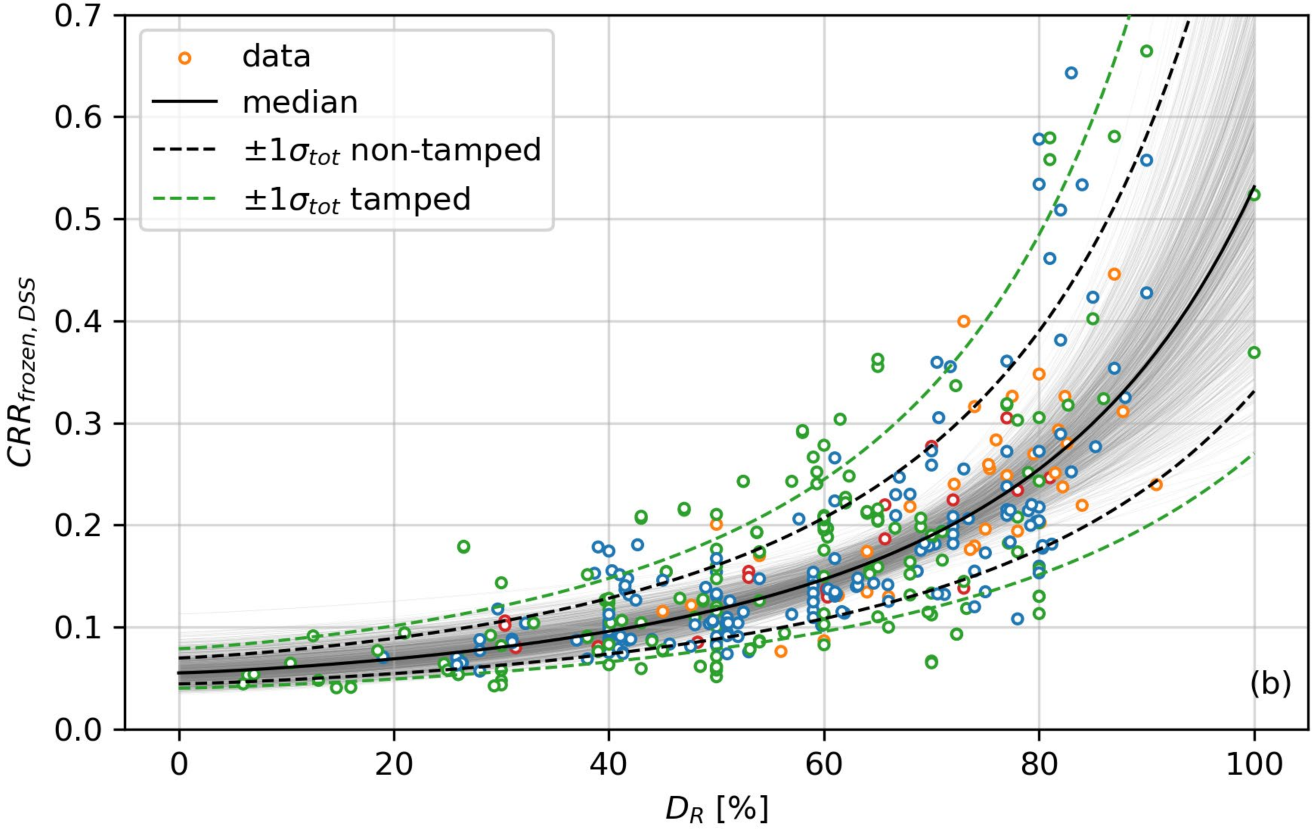
Triggering prior

Derived from laboratory cyclic tests

Model developed for equivalent condition of intact sample & direct simple shear testing



NGL NEXT GENERATION LIQUEFACTION

Modelling approach

Bayesian approach

Triggering “prior” P(T|S)

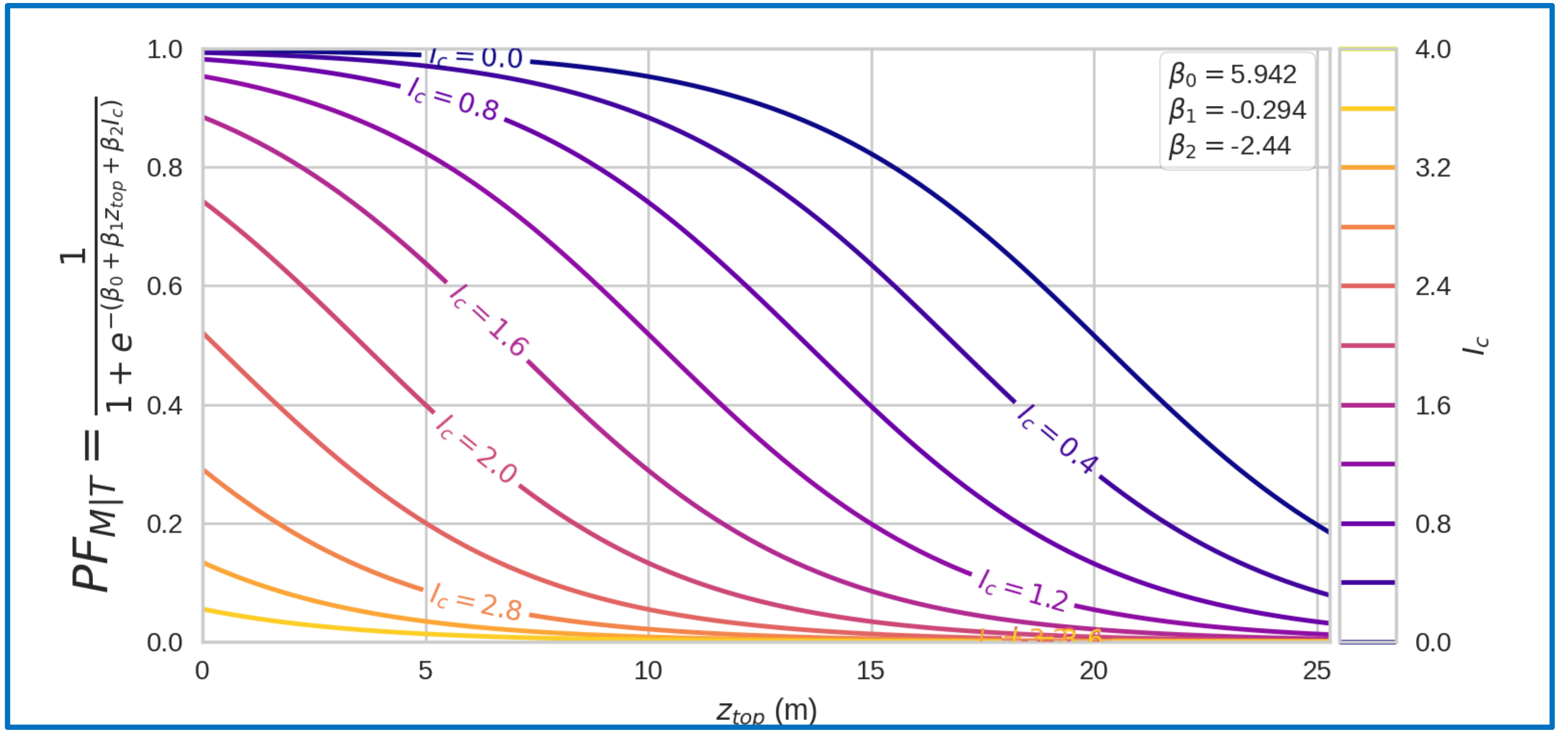
Manifestation models derived from case histories

Updated P(T|S) model

Probabilistic manifestation models

Derived from case history data using Bayesian updating

Layer Manifestation Model

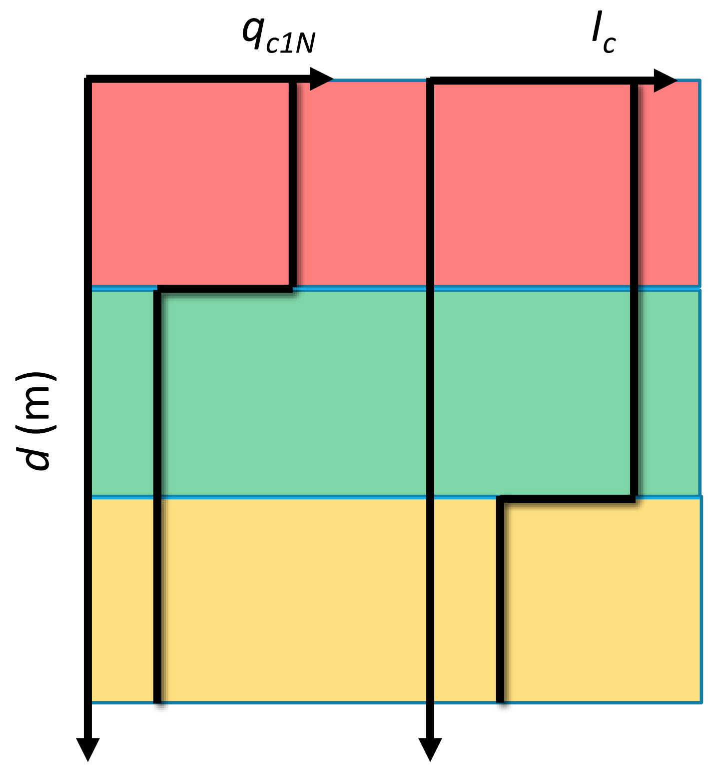


Probabilistic manifestation models

Model application

- Individual layers

Three Layer Profile

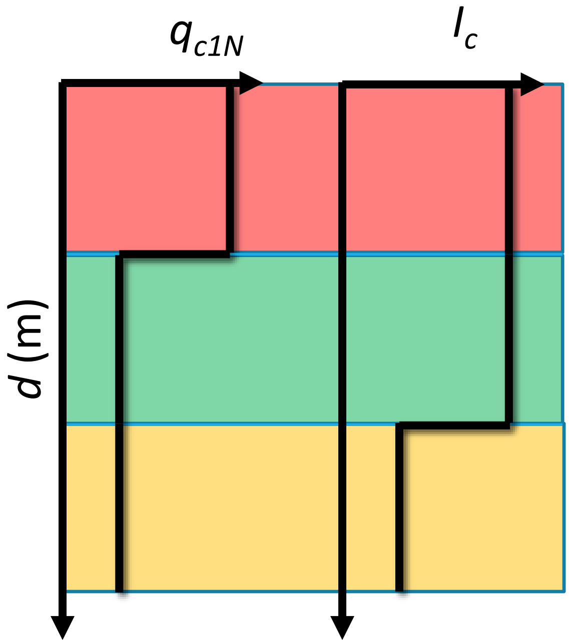


Probabilistic manifestation models

Model application

- Individual layers

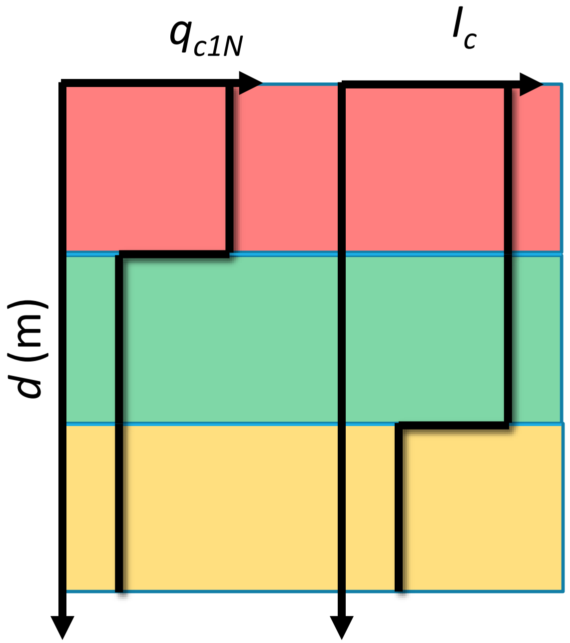
$$P\left[M_{j=1}^{L} | T_1^L, z_1, I_{c,1}\right]$$



Probabilistic manifestation models

Model application

- Individual layers



$$P\left[M^L_{j=1} | T^L_1, z_1, I_{c,1}\right]$$

Depth: $P\left[M^L_{j=1} | T^L_1, \boldsymbol{z_1}, \ldots\right] \sim high$ **Shallow**

$$P\left[M^L_{j=1,k} | T^L_{j=1,k}, x_{i=3,j=1,k}\right] \sim 0.2$$

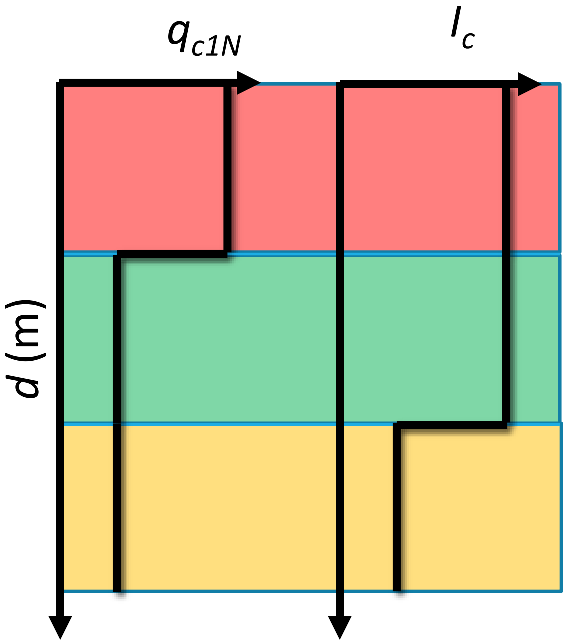
Probabilistic manifestation models

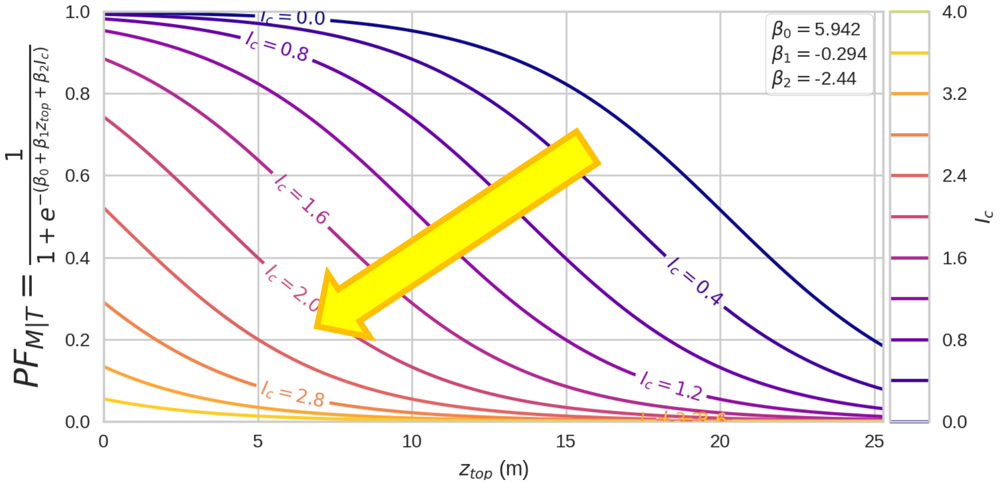
Model application

- Individual layers

$$P[M_{j=1}^{L}|T_1^L, z_1, I_{c,1}]$$

Depth:	$P[M_{j=1}^{L}|T_1^L, z_1, \ldots]\sim high$	**Shallow**
$\mathbf{I_c}$:	$P[M_{j=1}^{L}|T_1^L, \ldots, \boldsymbol{I_{c,1}}]\sim low$	**High**

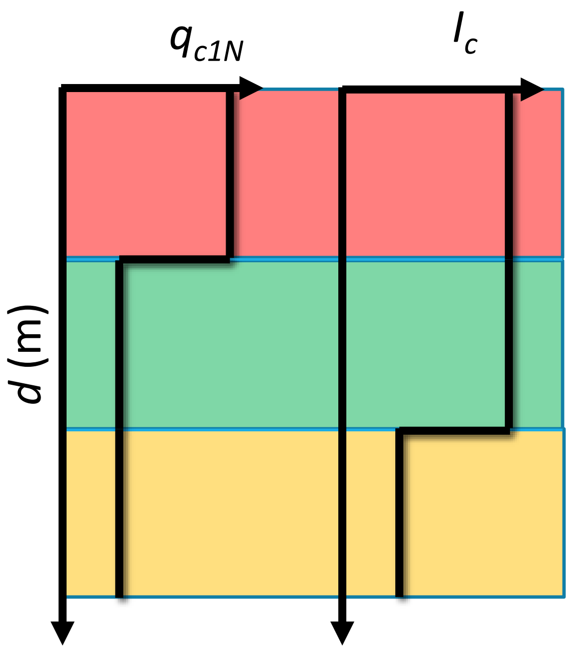




Probabilistic manifestation models

Model application

- Individual layers

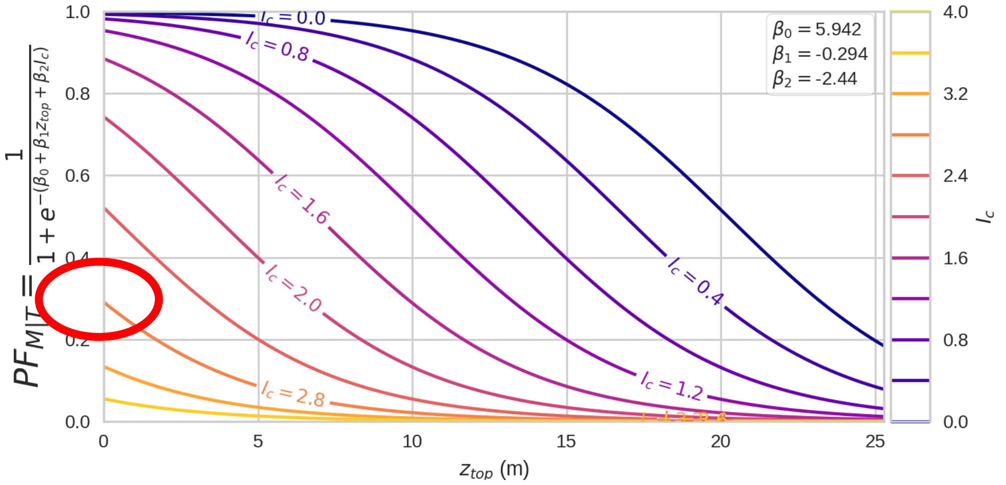


$$P\left[M_{j=1}^{L} | T_1^L, z_1, I_{c,1}\right]$$

Depth: $P\left[M_{j=1}^{L} | T_1^L, z_1, \ldots\right] \sim high$ **Shallow**

I_c: $P\left[M_{j=1}^{L} | T_1^L, \ldots, \boldsymbol{I_{c,1}}\right] \sim low$ **High**

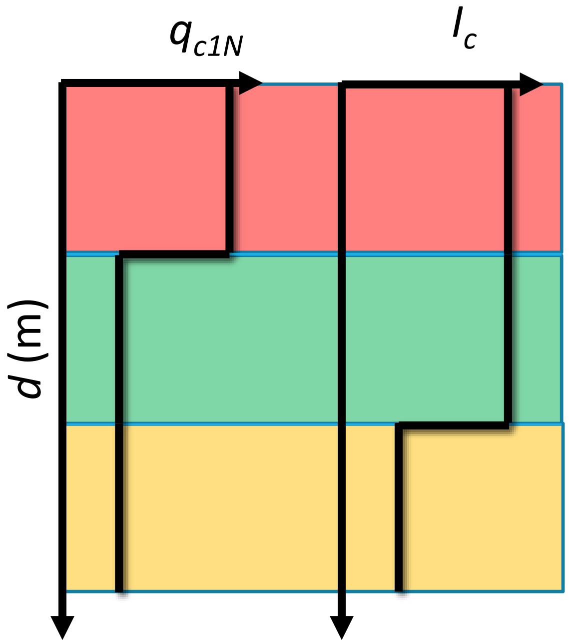
$$P\left[M_{j=1}^{L} | T_1^L, \ldots\right] = 0.3$$



Probabilistic manifestation models

Model application

- Individual layers



$$P\left[M_{j=1}^{L} | T_1^L, z_1, I_{c,1}\right]$$

Depth: $P\left[M_{j=1}^{L} | T_1^L, \boldsymbol{z_1}, \ldots\right] \sim high$ **Shallow**

I_c: $P\left[M_{j=1}^{L} | T_1^L, \ldots, \boldsymbol{I_{c,1}}\right] \sim low$ **High**

$$P\left[M_{j=1}^{L} | T_1^L, \ldots\right] = 0.3$$

$$P[T_1^L] \sim 0.2 \therefore P[M_1^L] = 0.06$$

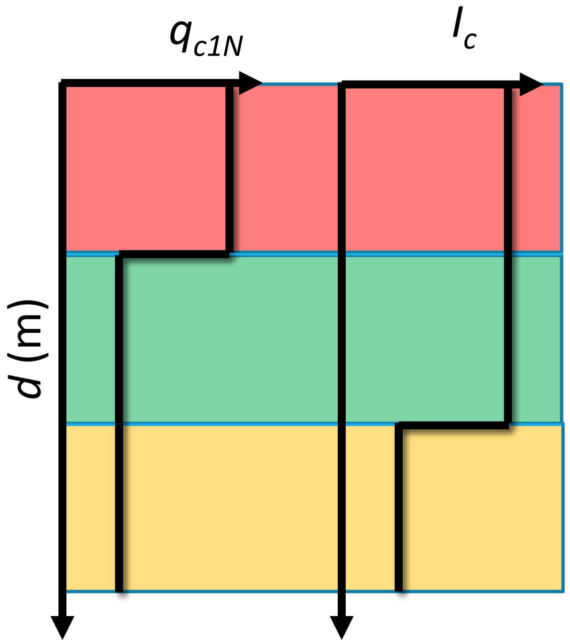
Probabilistic manifestation models

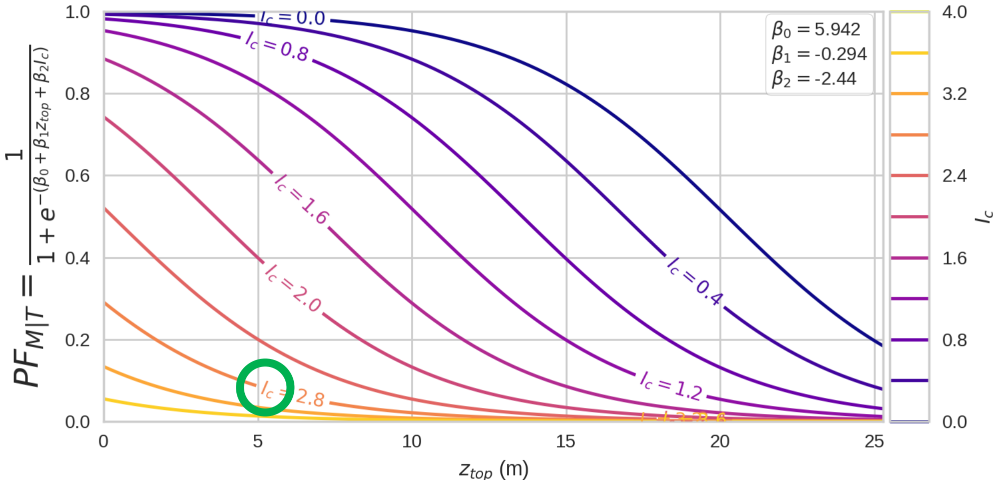
Model application

- Individual layers

$$P[M_{j=2}^{L}|T_2^{L}, z_2, I_{c,2}]=0.1$$

$$P[T_2^{L}]\sim 0.4 \therefore P[M_2^{L}] = 0.04$$





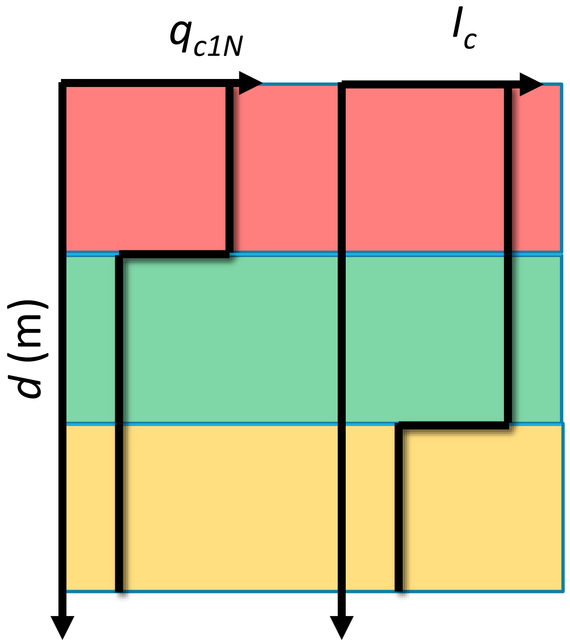
Probabilistic manifestation models

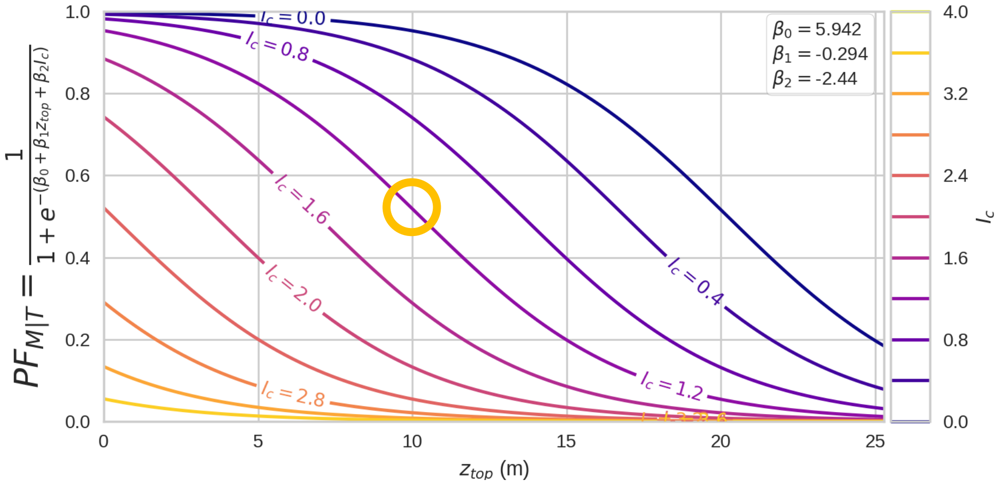
Model application

- Individual layers

$$P\left[M^{L}_{j=3} | T^{L}_{3}, z_3, I_{c,3}\right]=0.5$$

$$P[T^{L}_{3}]\sim 0.8 \therefore P[M^{L}_{3}] = 0.4$$

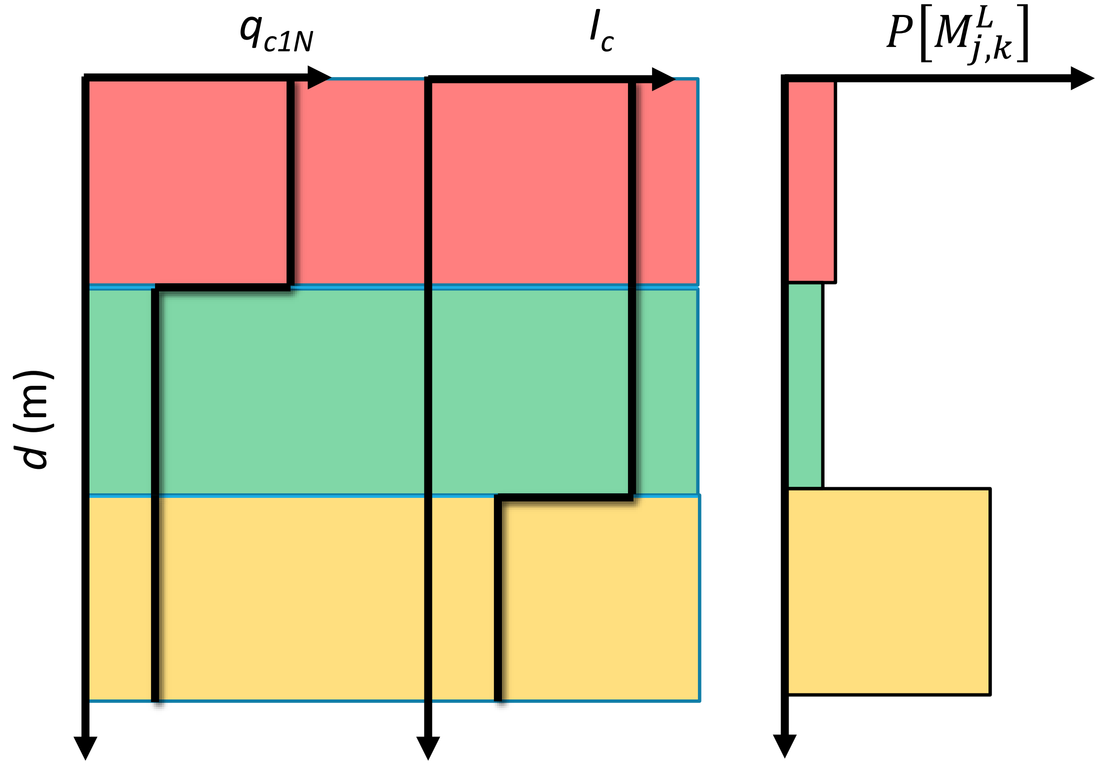




Manifestation models

Model application

- Individual layers
- Profile



$$P[M^P] = 1 - \prod_{j=1}^{N_L} (1 - P[M_j^L])$$

$$P[M^P] = 1 - (1 - 0.06) \cdot (1 - 0.04) \cdot (1 - 0.4)$$

$$P[M^P] = \mathbf{0.46}$$

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Manifestation models

Model application

- Individual layers
- Profile

Characterizes field performance more accurately than legacy models (in particular, fewer FPs)

Modelling approach

Bayesian approach

Triggering "prior" P(T|S)

Manifestation models derived from case histories

Updated P(T|S) model

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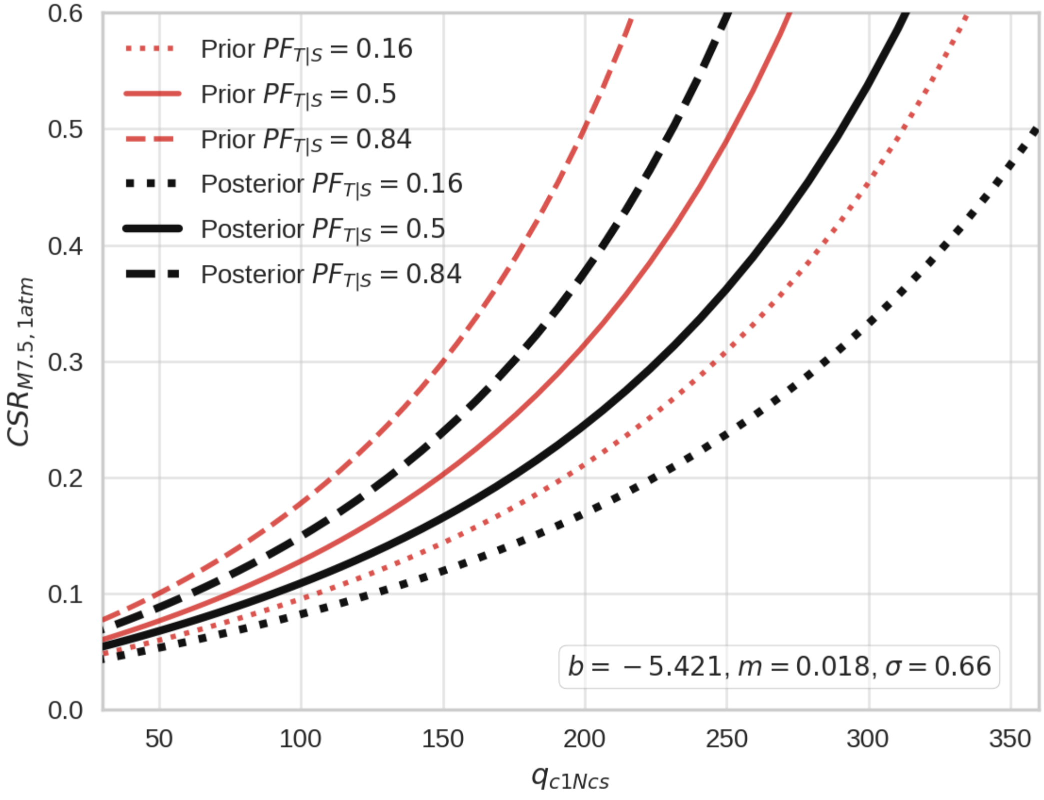
Updated triggering prior

Outcome of Bayesian updating

Slight downward shift, but difference from prior is not statistically significant

Influenced by assumed model components, especially fines correction



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Conclusions

- Modeling approach unpacks triggering from manifestation
- Ongoing work revising susceptibility model and fines corrections – may shift triggering and manifestation models due to coupling
- Advantages of framework: (1) defined uncertainties; (2) alignment with field performance; (3) well suited for liquefaction effects analysis

References

Databases, web tools:

Next Generation Liquefaction (NGL). https://nextgenerationliquefaction.org

NGL tools: DOI: 10.5281/zenodo.14004847

Upcoming workshop: EERI, May 17 2025, 1-5 pm, Oakland, CA. Link

NGL Database

Cubrinovski, M, A Rhodes, N Ntritsos, S Van Ballegooy (2019). System response of liquefiable deposits. *Soil Dynamics and Earthquake Engineering*, 124, 212-229.

Hudson, KS, KJ Ulmer, P Zimmaro, SL Kramer, JP Stewart, SJ Brandenberg (2023). Unsupervised machine learning for detecting soil layer boundaries from cone penetration test data, *Earthquake Engineering and Structural Dynamics*, 52(11),3201-3215.

Ulmer, KJ, KS Hudson, SJ Brandenberg, P Zimmaro, R Pretell, B Carlton, SL Kramer, and JP Stewart (2024). Next Generation Liquefaction models for susceptibility, triggering, and manifestation, Rev 1. U.S. Nuclear Regulatory Commission, *RIL 2024-13*. ML24268A229