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SCOPING ANALYSES TO INFORM SEISMIC RISK ASSESSMENT

A Case Study Using Nonlinear Time Domain Simulations

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October 20, 2020

SIMPSON GUMPERTZ & HEGER 

Engineering of Structures
and Building Enclosures

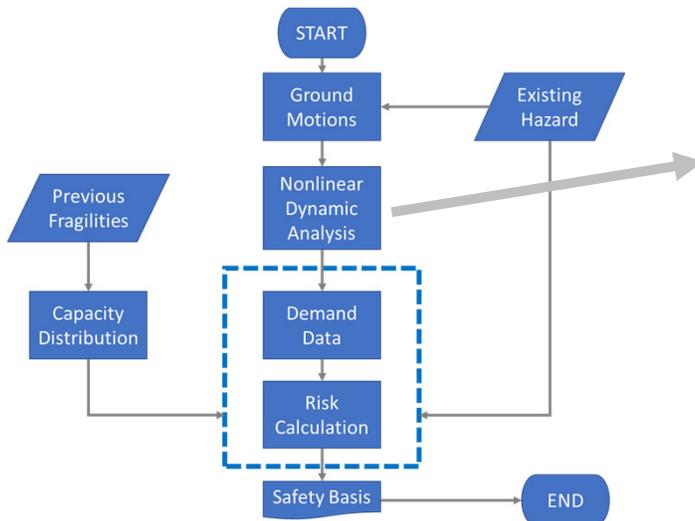
Outline

- Background
- Summary of Site and Structure
- Scoping Study Objectives
- Numerical Experiment Design
- Simplified Finite Element Model
- Randomization Sampling Process
- Simulations
- Preliminary Results
- Conclusions

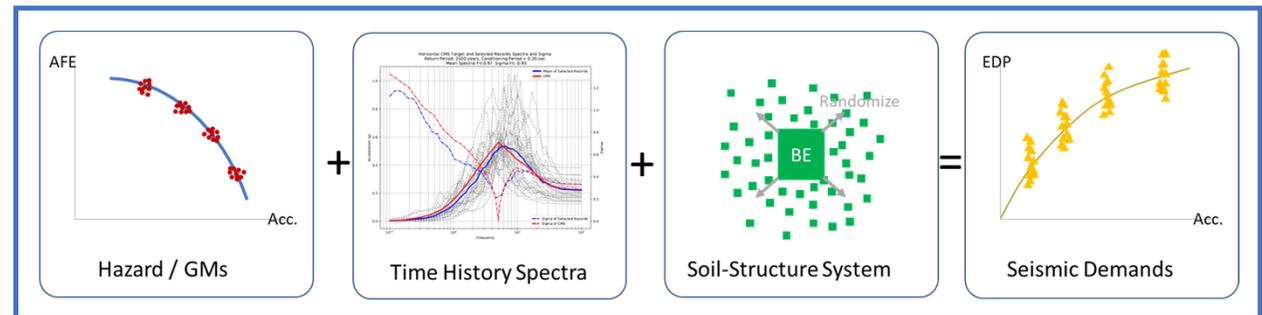
Background:

Seismic performance (risk) assessment involving probabilistic treatment of nonlinear phenomena raises old questions in new context.

Framework: Seismic Risk Assessment



Step: Probabilistic Seismic Demand Analysis



In order to achieve stable risk estimate, seismic demand addresses:

- How many GMs per stripe, and at which AFEs?
- How to condition GMs for risk-consistency?
- How many nonlinear SSI realizations, and with what RVs?
- How to pair GMs with SSI realizations?
- ...

Summary of Site and Structure

- Structure

- Credited for tertiary confinement function
- Squat reinforced concrete shear-wall structural system
- 1970s vintage design and detailing with capacity retrofits

} Limit State “C” →
deformation-based performance

- Site/Soil

- Layered strata of volcanic tuff, ~700 ft to firm rock, mesa formation
- Soft/weak layer ~50ft thick starting at ~50ft depth

} Nonlinear site effects

- Seismic Hazard

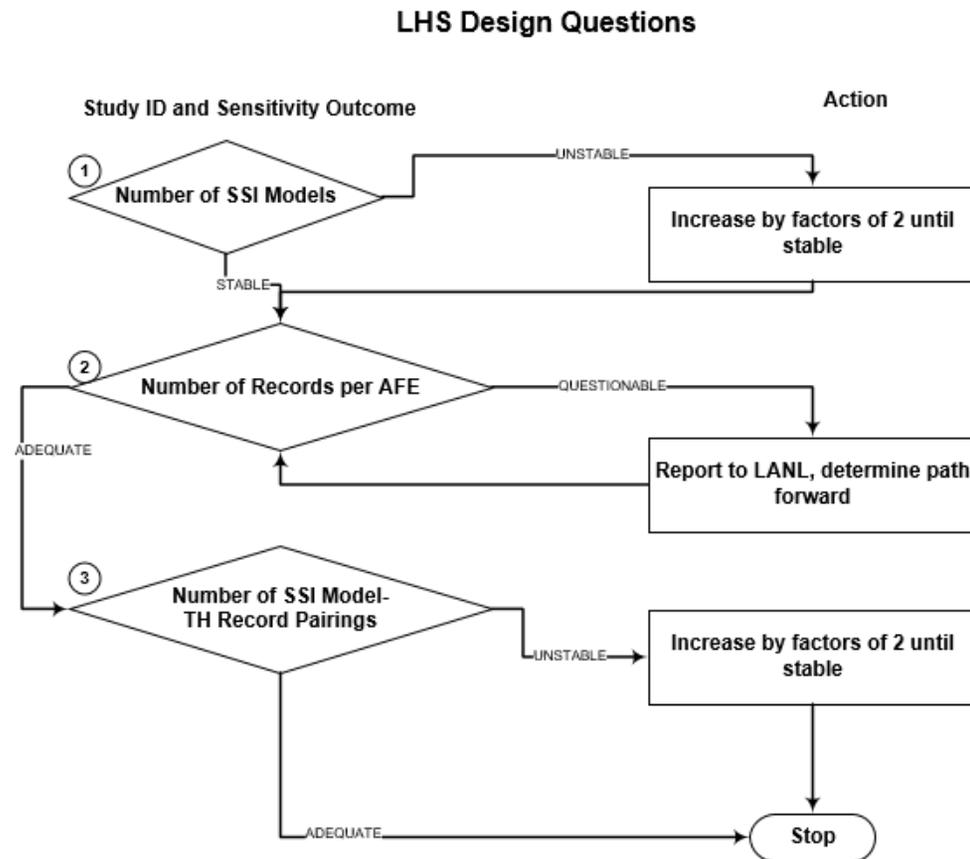
- Moderate-to-high seismicity
- Semi-recent PSHA results available at firm rock and at surface

Scoping Study Objectives

- Select a statistically stable number of probabilistic simulations
- Understand characteristics of soil and structure behavior that govern seismic risk
- Rank how uncertainty in soil and structure properties affect seismic risk estimates
- Identify ground motion levels that dominate seismic risk
- Inform cost-benefit selection basis of alternative seismic risk computation approaches and implementation details

Numerical Experiment Flowchart Example

- Primary objectives are to investigate
 - LHS Design Questions (Statistically Stable?)
 - Risk Process Questions (Robust, accurate?)
- Availability of tool allowed investigating other questions
 - Build confidence and streamlined process
- Secondary objectives
 - Influence of input parameter variability on behavior and response distribution
 - Sensitivity to sampling decisions
 - Risk-importance of ground motion levels
 - Cost-benefit of risk process implementation decisions



Numerical Example Process for LHS Design Questions

Numerical Exp. Sensitivity Study Examples

- The following table shows an implementation of the roadmap design

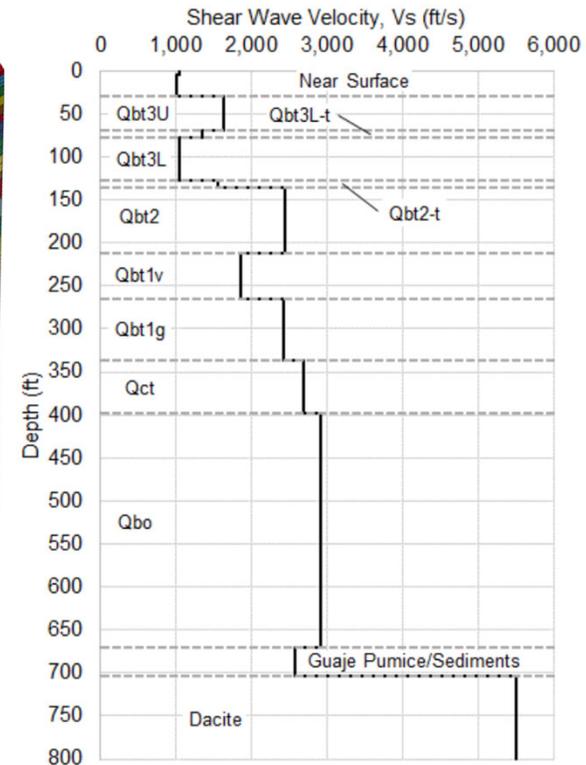
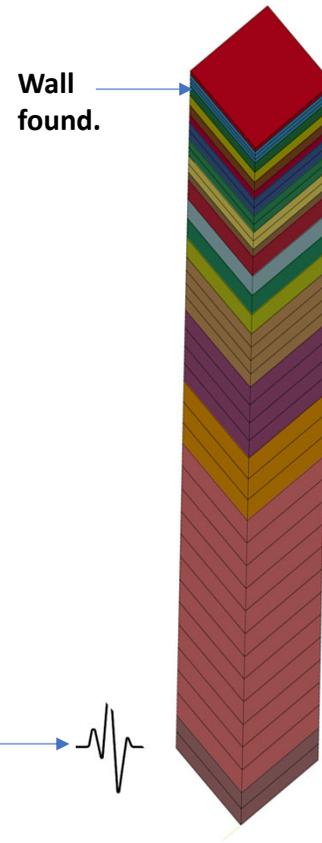
LHS Design Questions

Study ID	Subject	Base Case	Alt. Case(s)	Basis
1	Number of SSI models, N	Simulations of 1 TH x 30 models Run all AFEs u.n.o. Will rely first on the 4E-4 and 4E-5 AFE runs for determining N	1 TH x 60, 120, etc. models until convergence	Target N that results in stable outcome for a given EQ scenario. Select 1 broad-band TH for Approach 2A. Select 2 THs (LH and HF spectra) for Approach 2B. Favor records with longer durations. Favor using the same seed TH in all AFEs. Examine stability of distributions and P_f . Confirm that selected N is stable using an alternative TH input after the fact. Perform the confirmation at the higher AFE level where NL response is stronger.
2	Number of Records per AFE, M	1 BE SSI model x 30 H1 component records May run only 4E-4 and 4E-5 AFEs	1 BE SSI model x 30 H2 component records	Target M for each approach that results in stable outcome for a given SSI model. Examine stability of distributions and P_f .
3a	LHS sample size Min. number of pairings, K	N x M LHS with K = 1 pairings Run 4E-4 and 4E-5 AFEs	NxM simulations (full pairing) for reference N x M LHS with K = 2, 4, etc. pairings until convergence	Pair each SSI models with 1, 2, 4, etc. THs each until stable output is reached.
3b	LHS sample size Final number of pairings, K	Converged case from 3a	Reshuffle the SSI-TH pairing	If the min. number from 3a does not converge, increment until stability.

For the remaining simulations, use N SSI models, M pairings, and K THs as determined above u.n.o. (unless noted otherwise).

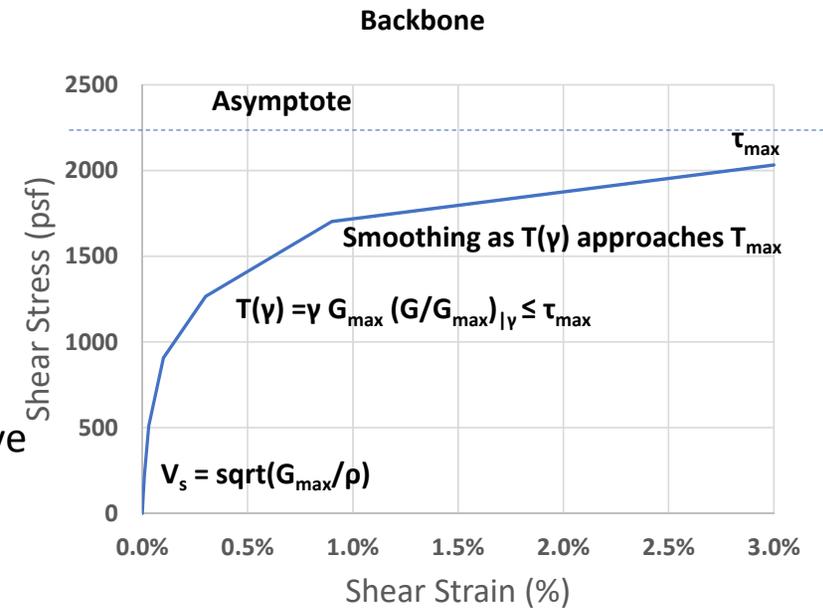
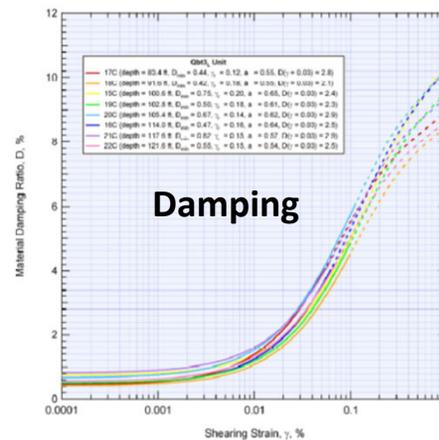
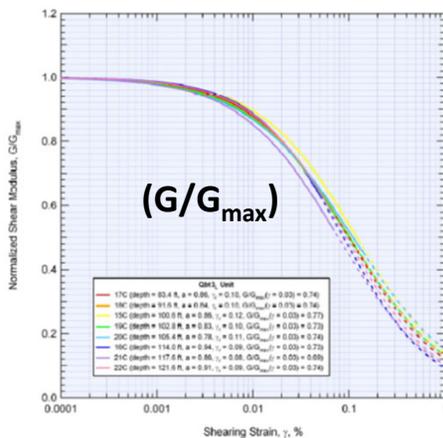
Simplified FE Model

- FE model LS-DYNA – same software platform for full 3D FE model
- 1D soil column with horizontally-layered strata using brick elements
- SDOF shear spring representing exterior wall embedded near surface
- SDOF mass tributary to wall segment
- One horizontal component of time-history input
 - Lysmer damper at base of soil column to excite the model



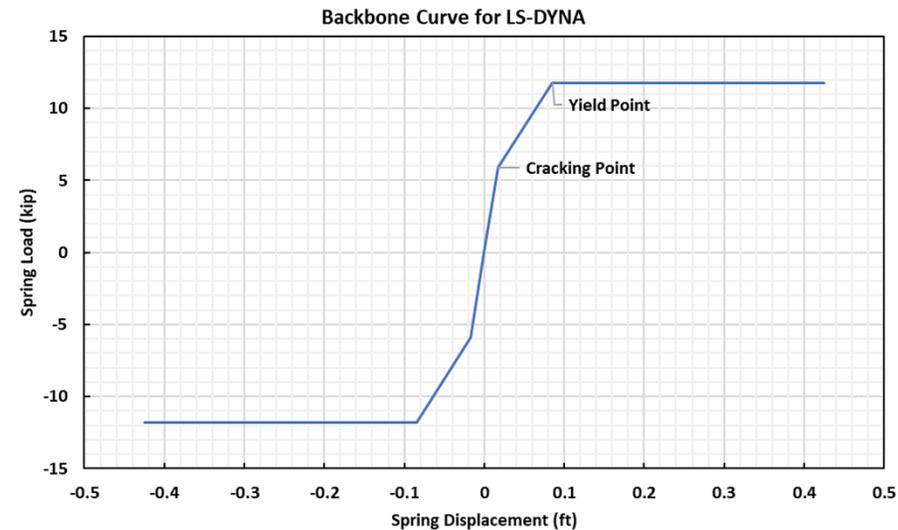
Elements of Soil Material Curves

- Backbone curve defined by G_{\max} , G/G_{\max} curve, and τ_{\max}
- G_{\max} defines V_s , the shear wave velocity at small strains
- G/G_{\max} curve controls the nonlinear backbone curvature
- τ_{\max} controls asymptote at large strain
 - Hyperbolic smoothing done to transition to asymptote
- Unloading-reloading defined by non-Masing damping curve



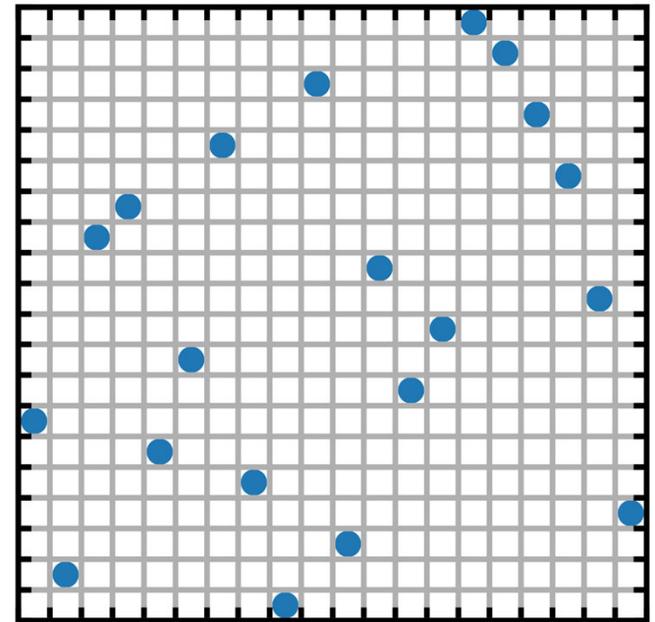
Elements of Wall Nonlinear Curve

- Backbone curve defined by D_{cr} , F_{cr} , D_y , and F_y
 - Displacements at cracking and yield
 - Strengths at cracking and yield
- No softening branch for backbone
 - Limit-state of interest is onset of strength loss
 - Corresponding displacement is part of capacity evaluation
- Unloading-reloading defined by K_u
 - K_u is the ratio of unloading stiffness to F_{cr}/D_{cr}
 - Perfectly pinched behavior after unloading until reloading



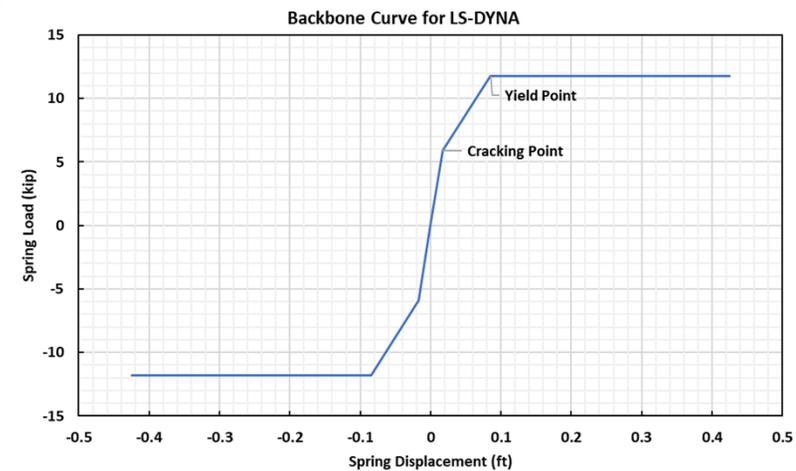
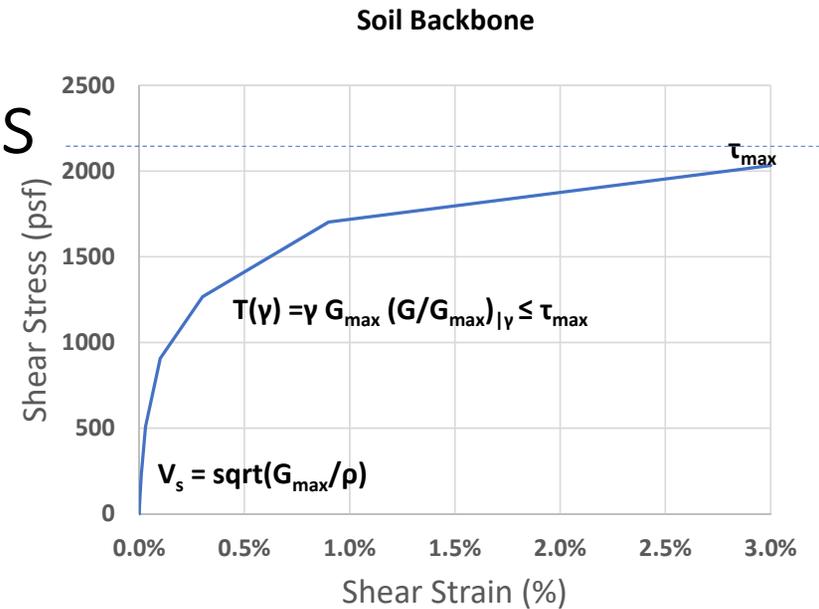
Randomization Scheme

- Need an “intelligent” sample of manageable size
- Developed a Latin Hypercube Simulation approach
 - Determine appropriate sampling distribution for each variable
 - Truncate distribution as applicable to avoid sampling non-physically valid extreme values
 - Subdivide distribution into equal-probability bins
 - Select one random variable realization per bin
 - Pair sampled variables together to generate random models
 - Pairing can be at random or optimized for space filling
 - Pairing should account for applicable physical correlation
 - Review resulting samples for potential anomalies
 - Sample too small and “intelligent” to leave it all to chance



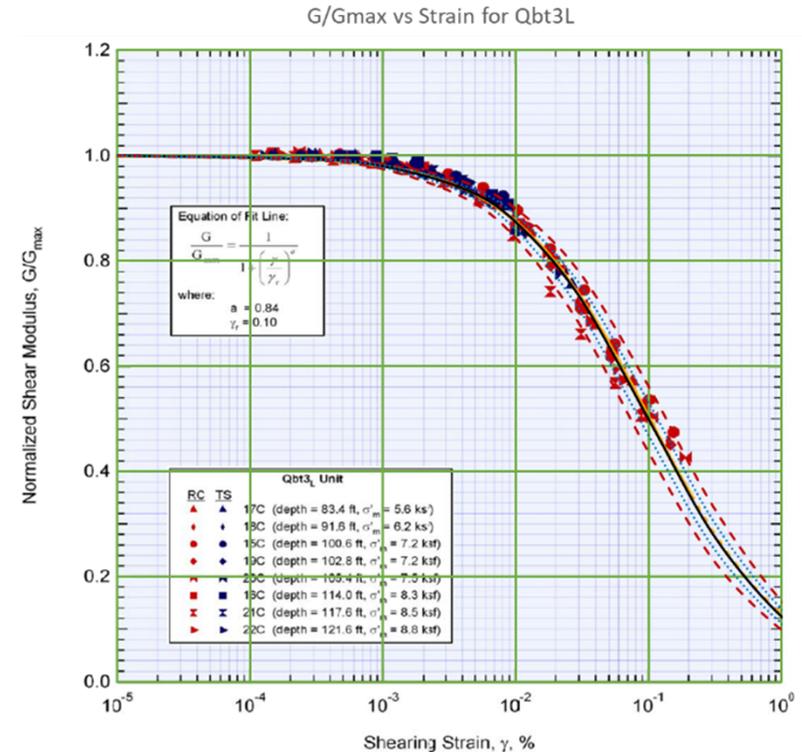
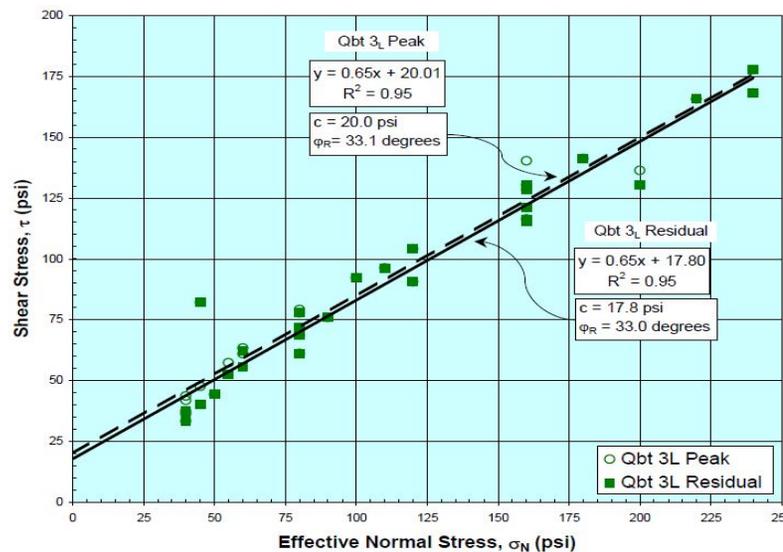
Randomizing Material Curves

- Soil Backbone curve
 - LHS-sampled G_{\max} , G/G_{\max} curve, and τ_{\max}
 - Imposed positive correlation on G_{\max} vs. τ_{\max}
- Soil Unloading-reloading
 - LHS-sampled Damping curve
 - Imposed negative correlation on G/G_{\max} vs. Damping
- Soil V_s profile with depth
 - Imposed strong positive correlation between adjacent layers (consistent with site data)
- Wall Backbone curve
 - LHS-sampled D_{cr} , F_{cr} , D_y , and F_y
 - Imposed positive correlation on D_{cr} vs. D_y
- Unloading-reloading
 - LHS-sampled K_u

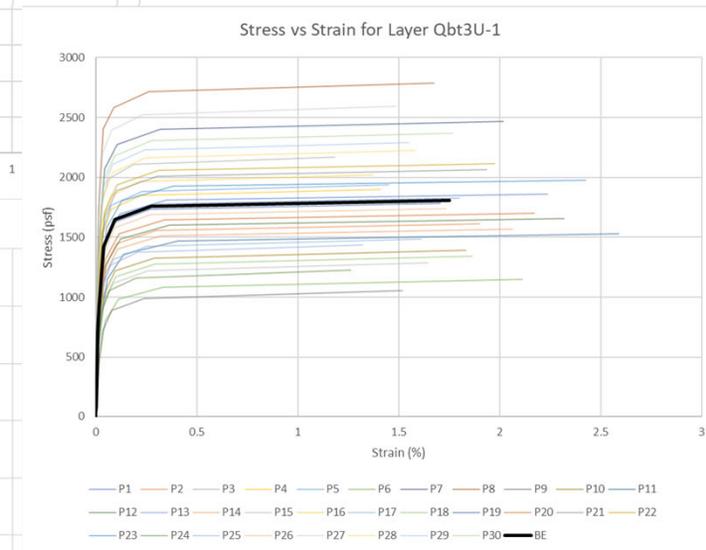
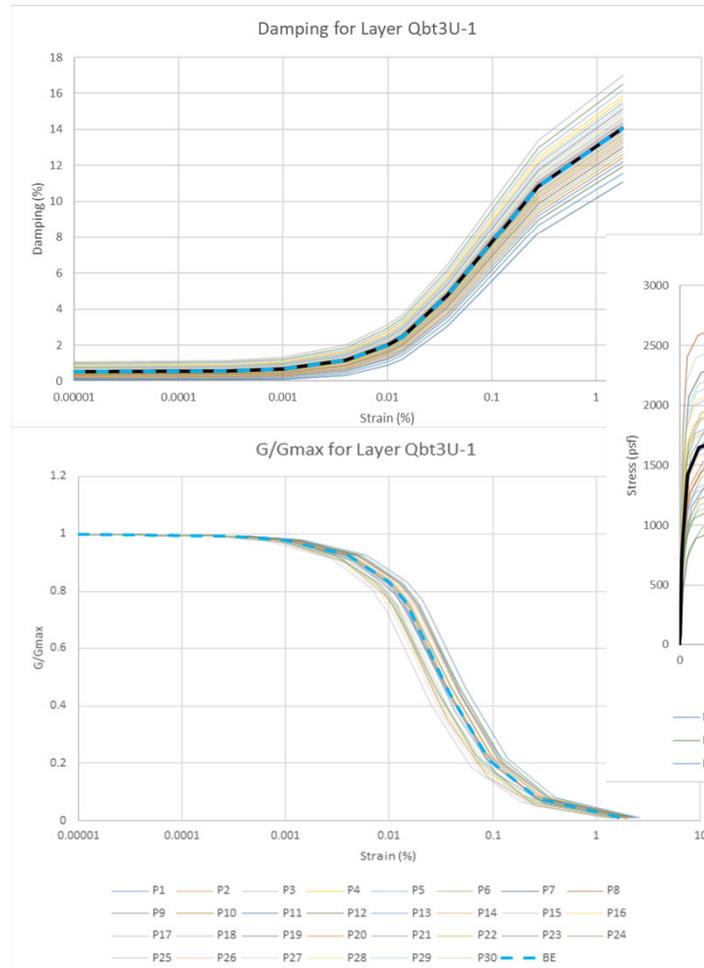
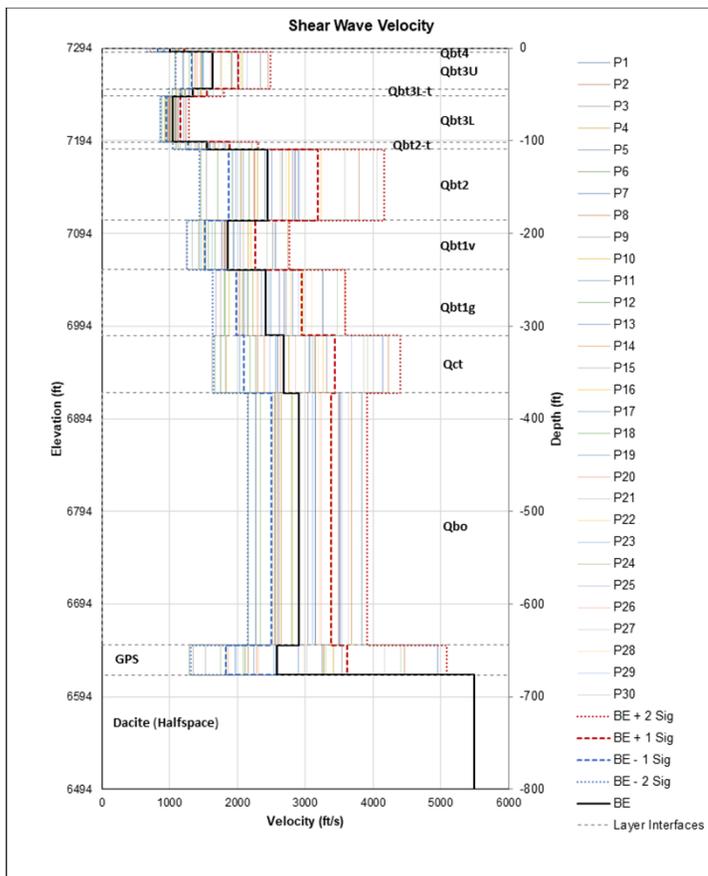


Example Site-Specific Variability Estimates

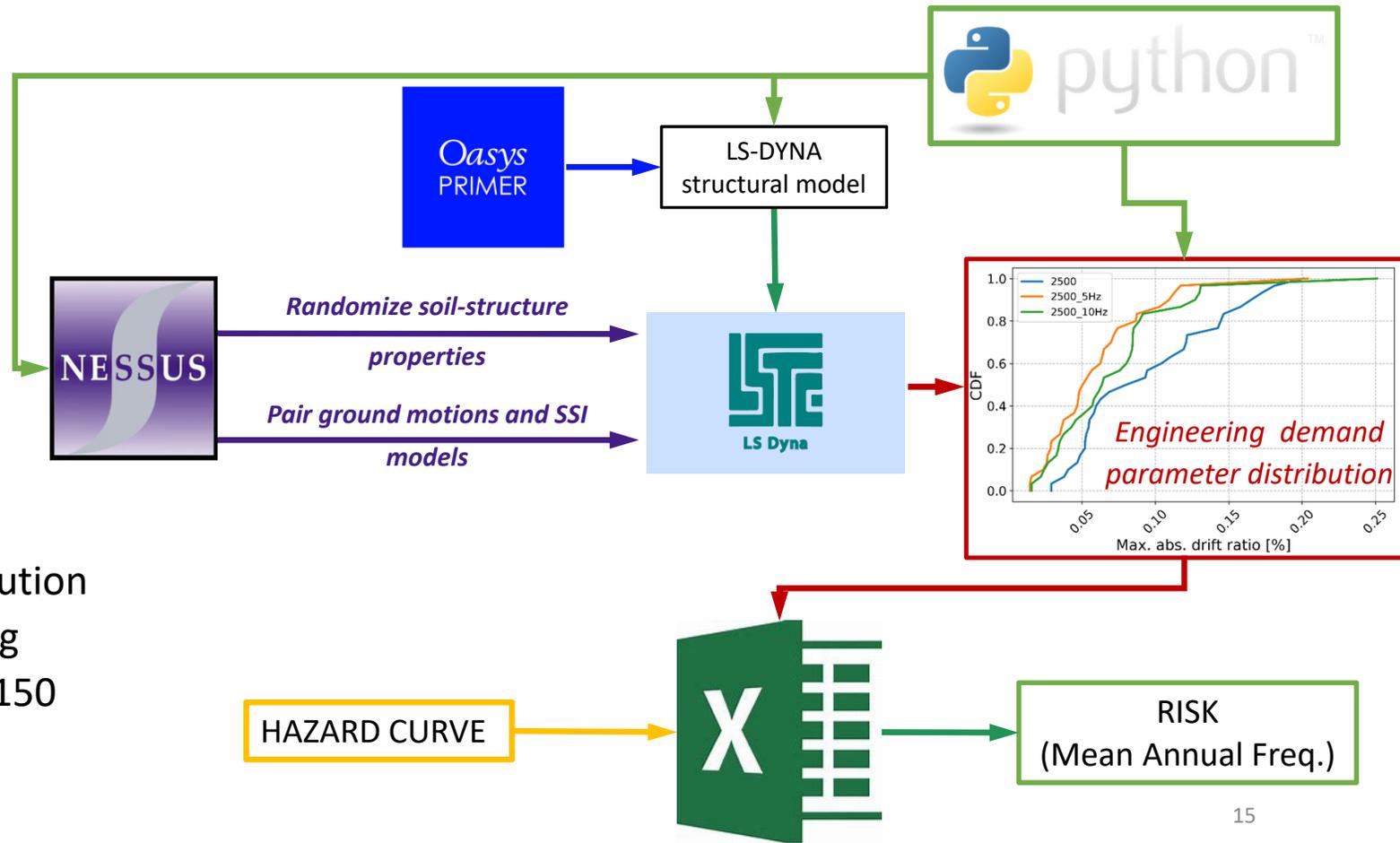
- G/G_{max} curves: fit distribution bounds to resonant column test data
- τ_{max} : digitized direct shear test data to estimate σ



Example Randomized Soil Material Input



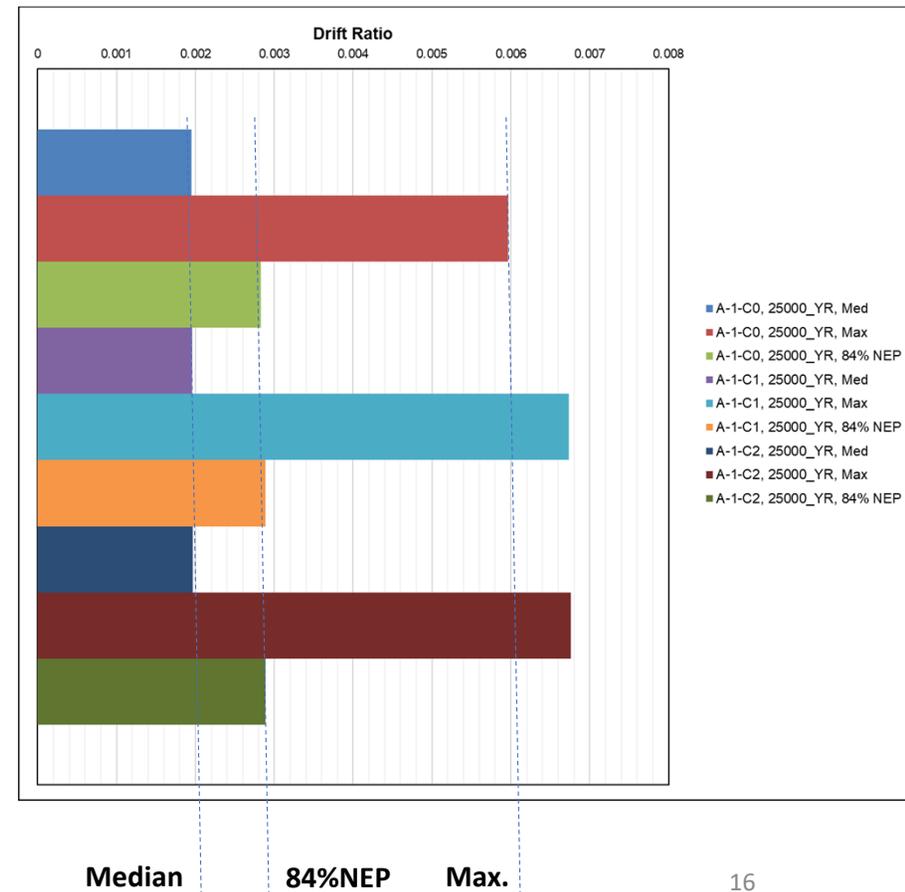
Simulation on LANL HPC Cluster



- Streamlined execution
- Parallel processing
- 60 simulations ~ 150 minutes

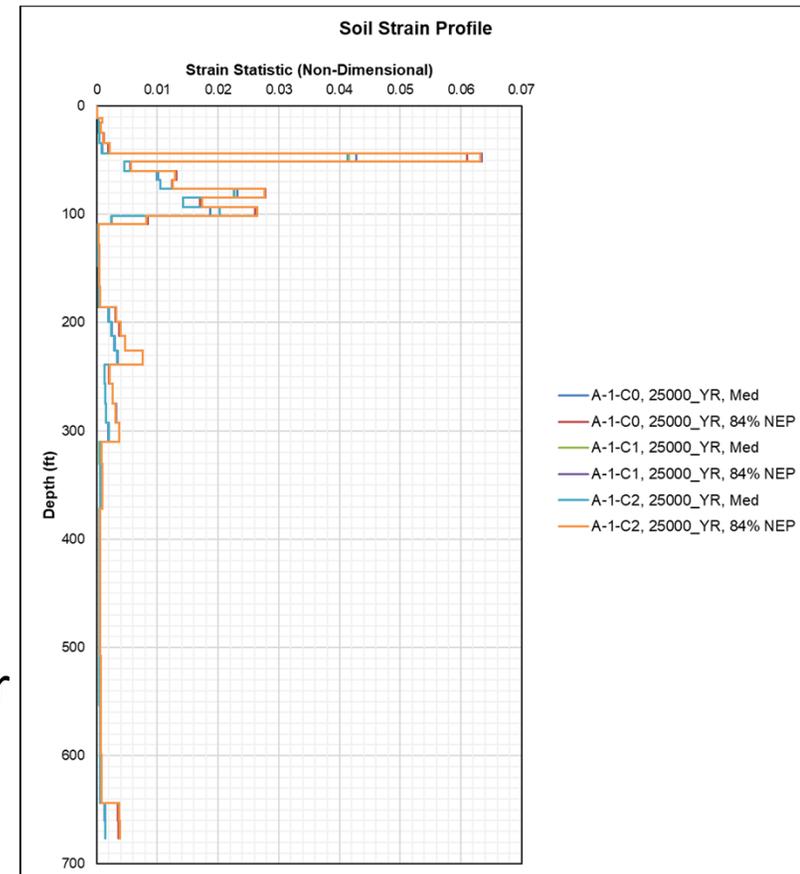
Preliminary Results: No. of Randomized Models

- Wall drift distributions shown for 30 (C0), 60 (C1), and 120(C2) SSI models at 25,000-yr input motion
- Results for 60 and 120 models are “identical”
- Results for 30 models show slight difference in the max drift
 - Median and 84% NEP drifts are insensitive



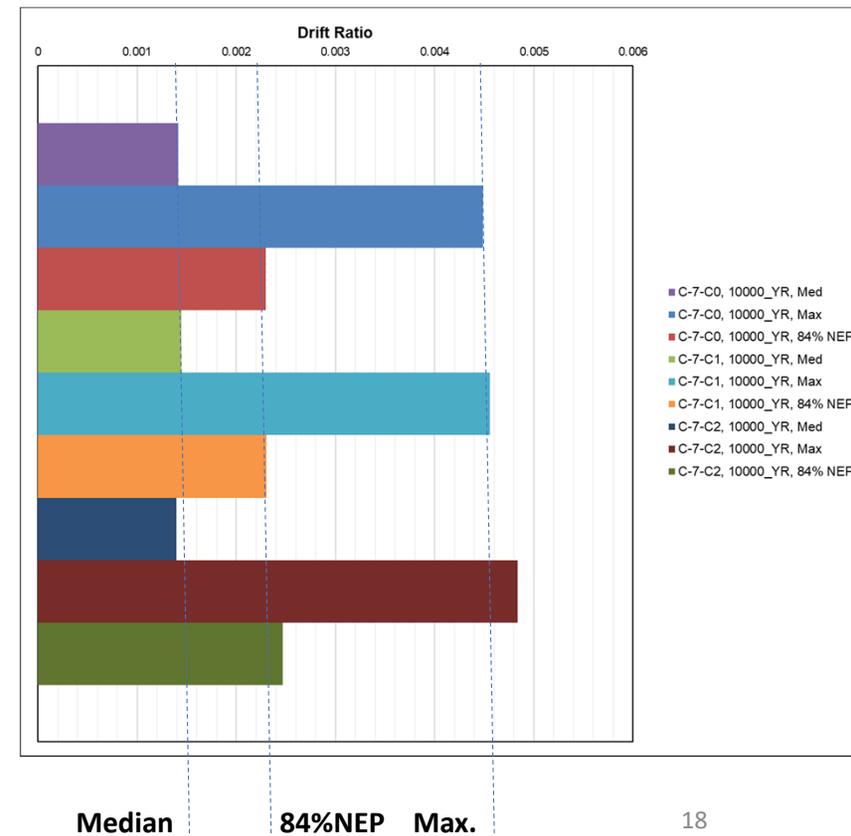
Preliminary Results: No. of Randomized Models

- Soil strain distributions shown for 30 (C0), 60 (C1), and 120(C2) SSI models at 25,000-yr input motion
- Results for 60 and 120 models are “identical”
- Results for 30 models show slight differences
 - Likely have little effect on risk assessment
 - Can be favored in full SSI analysis on cost-benefit basis
- For rest of experiment, use 60 SSI models to isolate effect of sample size from those of other sensitivity study inputs



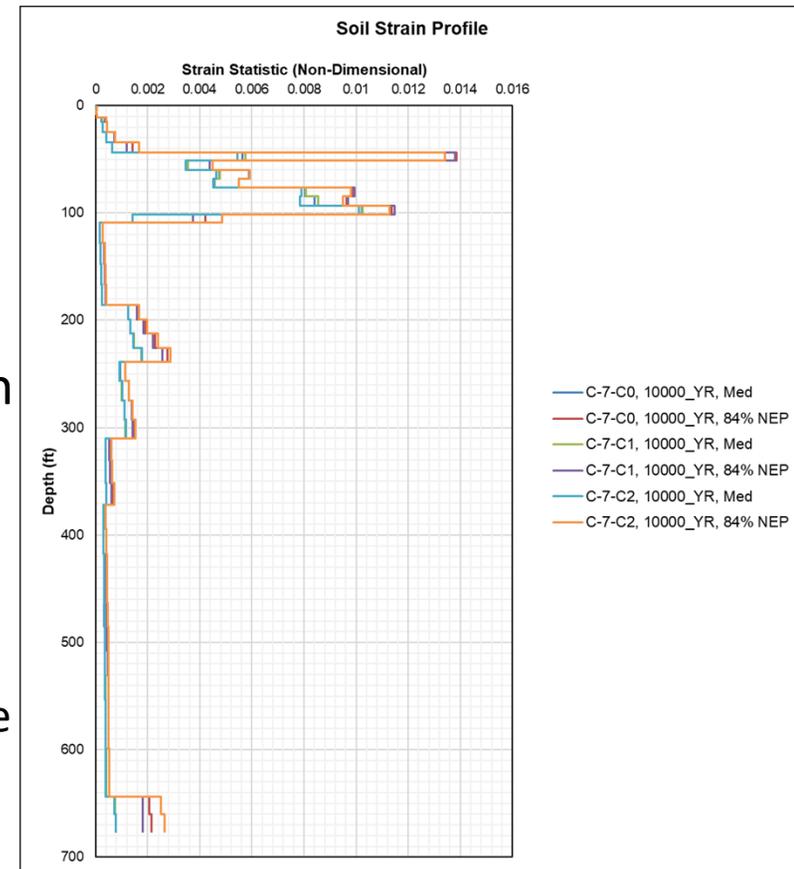
Preliminary Results: Distribution Truncation

- Wall drift distributions shown for 1.65σ (C0), 2σ (C1), and No (C2) truncation at 10,000-yr input motion
- Median drifts are “identical” for all cases
- 84% NEP and max drifts are “identical” for the two truncation cases, slightly higher for no truncation
- Sensitivity to truncation is as expected, no excessive increase if no truncation
- No significant sensitivity to this decision
 - Truncation between 1.65σ and 2σ seems reasonable and results in comparable output



Preliminary Results: Distribution Truncation

- Soil strain distributions shown for 1.65σ (C0), 2σ (C1), and No (C2) truncation at 10,000-yr input motion
- Median strains are “identical” for all cases
- 84% strains show minor sensitivity to truncation
- Sensitivity to truncation is as expected
 - Strain range decreases with more truncation
 - No excessive increase beyond some truncation limit
- No significant sensitivity to this decision
 - Truncation between 1.65σ and 2σ seems reasonable and results in comparable output



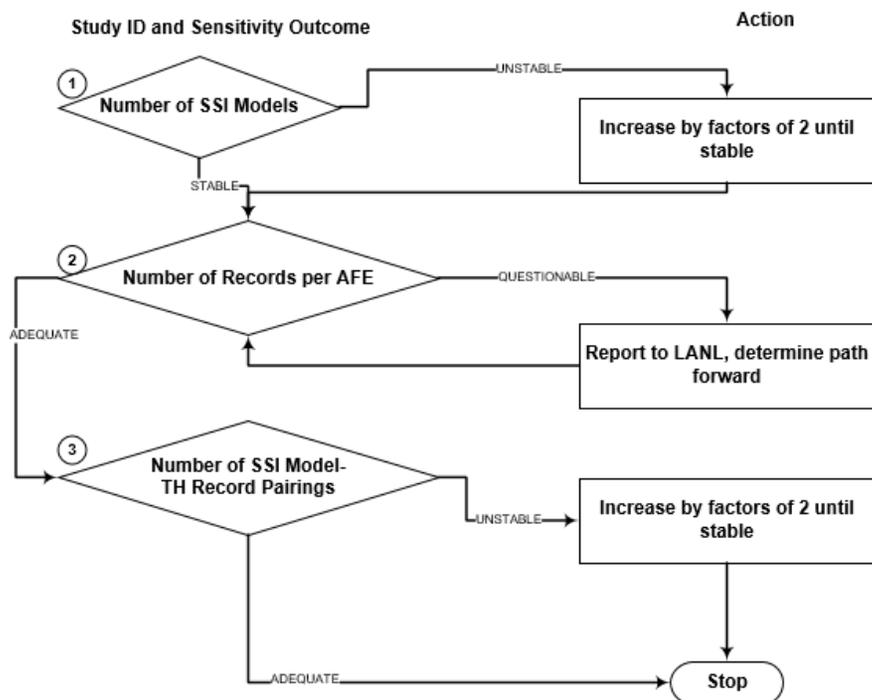
Conclusions

- Common simplifications and idealizations of hazard and probabilistic modeling and risk quantification methodologies may lead to excessive bias in risk estimates
 - Especially in nonlinear time-domain analyses - conventional “rules of thumb” may not apply
- In-depth scoping analysis studying their relative effects for one such DOE facility
 - A simplified “proxy” 1D computational FE model of the facility
 - An efficient series of sensitivity studies systematically designed to answer five question groups
- Numerical experiment expected to conclude in November 2020
- Insights are being used to optimize the probabilistic analysis of the computationally intensive 3D FE simulations needed for risk assessment
- Demonstrates feasibility of relatively simplified analysis models to economize complex seismic risk calculations that may otherwise appear intractable

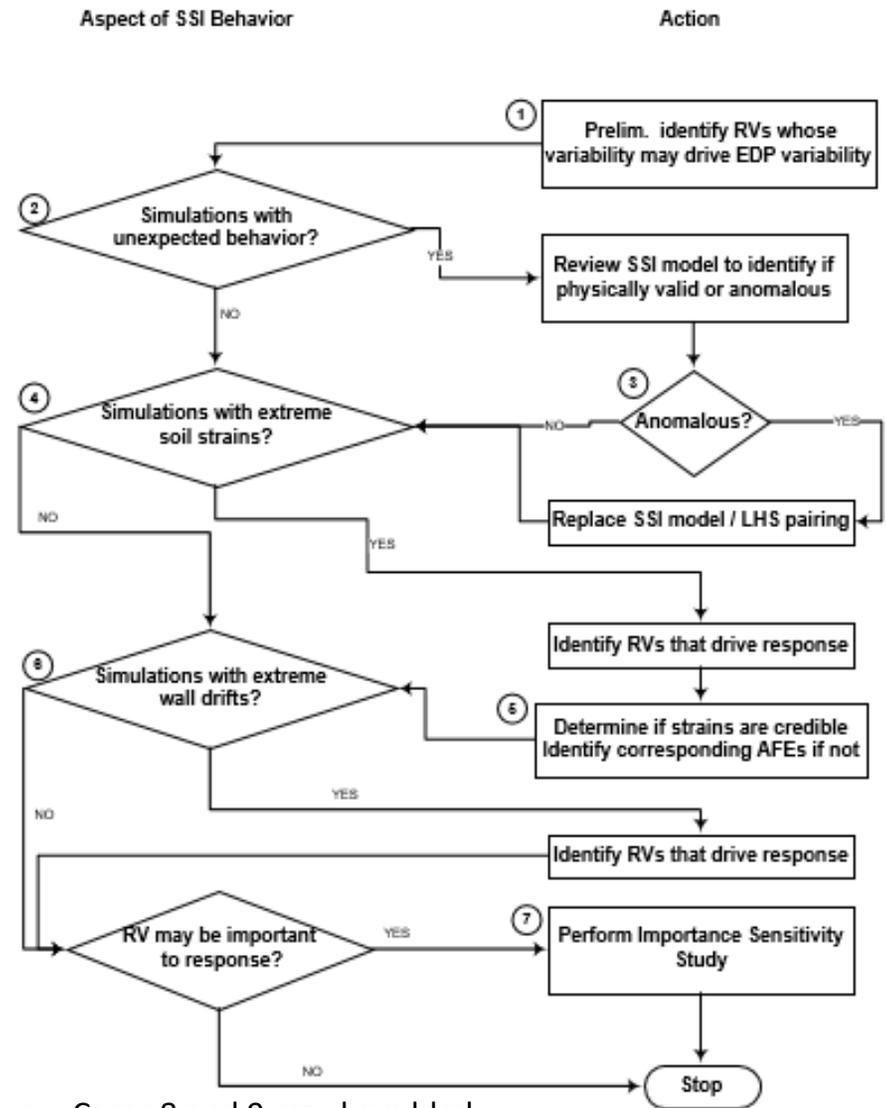
Thank You

Numerical Experiment Roadmap (cont.)

LHS Design Questions

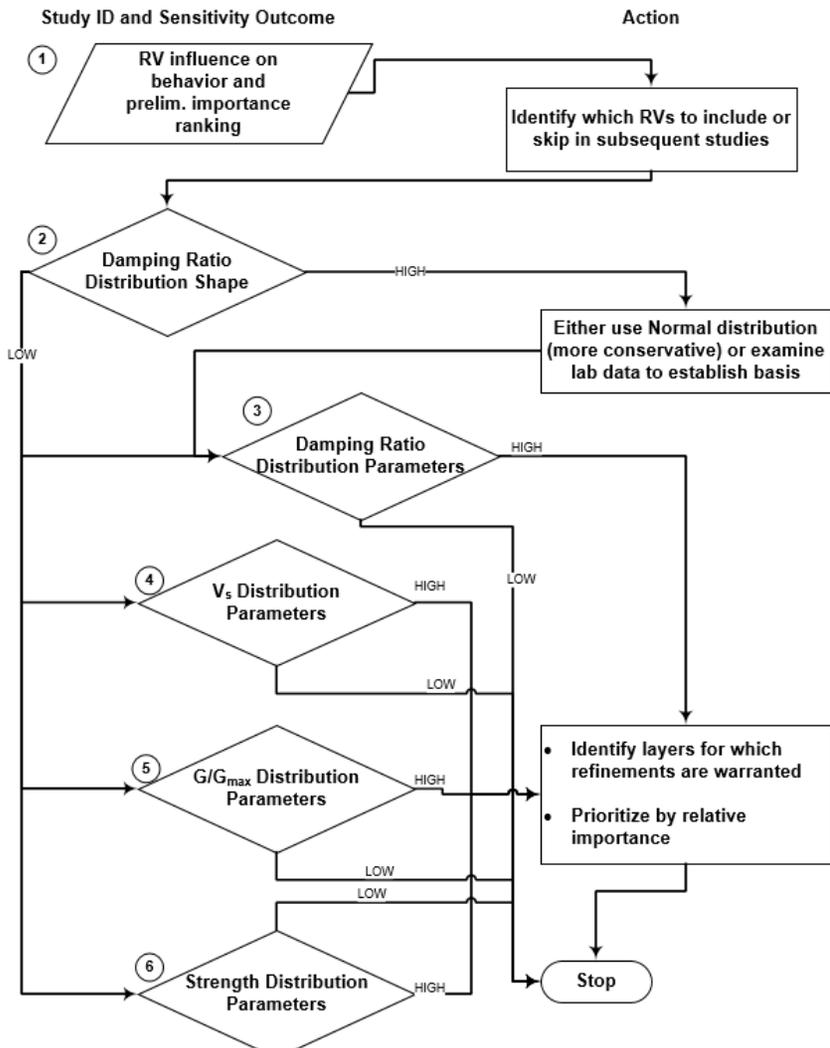


SSI Behavior Questions



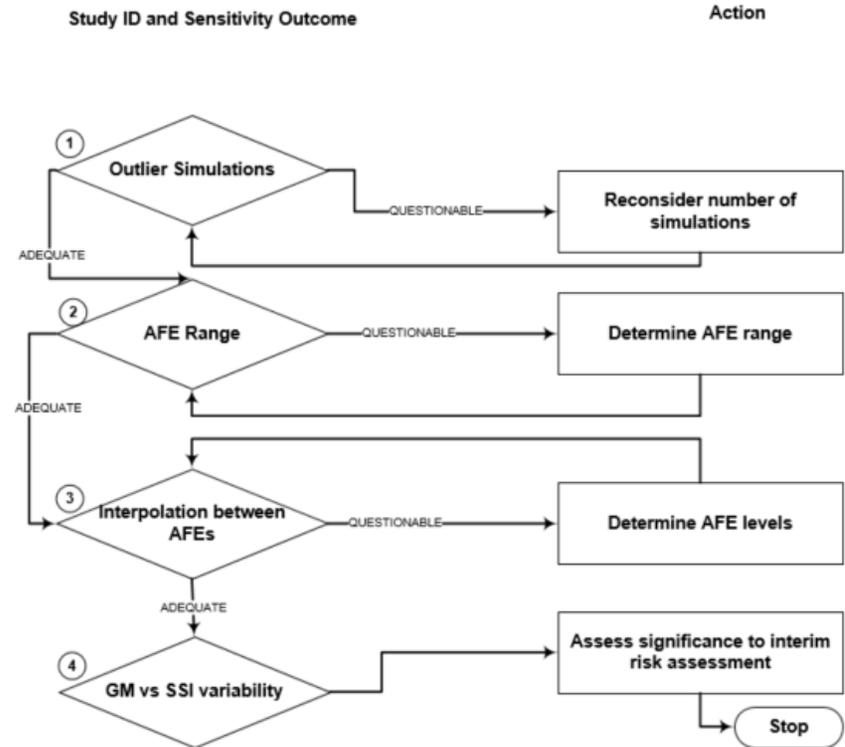
- Cases 8 and 9 may be added.

Randomization and Sampling Questions



- Case 7 may be added

Accuracy and Robustness Questions



- Case 5 may be added.

Risk Process Questions

- No flowchart.

SSI Behavior Questions

Note Number	Objective	Approach	Basis	Decision Factor
1	Identify RVs whose variability clearly does not influence variability in the response and RVs who may* have influence	Use results from LHS design questions (1 TH x N SSI model simulations, THs TBD) Use 4E-4 and 4E-5 AFEs Review correlation plots between EDPs (drift, soil strains) and input RVs	Focus on effects of RV variability, not TH. RVs that have weak correlation do not drive the response. RVs that have considerable correlation may drive the response (or may not).	Correlation factors
2	Identify RV combinations that lead to unexpected outcomes	Use results reviewed in #1 Compare results to those using BE SSI model and same TH input	Review individual simulations compared to BE re: concentration of response in soil vs. structure.	Max. strain profiles + wall drifts
3	Identify anomalous RV combinations, if any	Review RV combinations identified in #2	Double-check that soil profile and/or structure model represent valid RV combinations.	Not a specific parameter.
4	Identify RVs that may* drive concentration of response (EDP) in specific soil layers	Use results reviewed in #1	Typically, examine effects of soil properties up to layer in question plus one layer above.	EDP-RV Correlation
5	Identify AFE levels at which soil strains from SSI analyses may become not credible	Use results reviewed in #1 but include all AFEs	Identify number of THs in which a max. strain threshold is exceeded per AFE. Report layer(s). Report for multiple candidate thresholds. Lowest threshold = -1%; highest TBD.	Max. soil strain
6	Identify RVs that may* drive concentration of response (EDP) in the structure walls	Use results reviewed in #1	The influences of all soil layer and structure properties need to be examined.	EDP-RV Correlation
7	Establish preliminary rank of RV importance	Sensitivity study for RVs of potential importance Base case: Results reviewed in #1 Alternate cases: Rerun SSI simulations while setting one RV at a time to be deterministic Compare difference in EDP distributions	RVs whose elimination from LHS leads to larger effects on EDP distributions rank higher in importance.	Wall drifts Soil strains in layer(s) that may determine highest usable AFE

* RVs that show strong correlation with output EDPs may be the driver of EDP variability, but may only be physically correlated with the driving RV.

SSI Behavior Questions (cont.)

Note Number	Objective	Approach	Basis	Decision Factor
8	Preliminary sensitivity to wall unloading stiffness	Deterministic: BE, UB, LB	Explore whether wall drift distributions show influence.	Max. wall drift
9	Sensitivity to wall unloading stiffness	Deterministic vs. probabilistic	Compare wall drift dist. From SSI simulations where is explicitly randomized vs. deterministic.	Max. wall drift

* RVs that show strong correlation with output EDPs may be the driver of EDP variability, but may only be physically correlated with the driving RV.

Randomization and Sampling Questions

Study ID	Subject	Base Case	Alt. Case(s)	Basis	Decision Factor
1	Identify and prioritize sensitivity study cases.	N.A. Previously completed analyses		Review preliminary importance ranking and influence of variabilities in input RVs on SSI response to <u>determine which sensitivity cases to perform of the ones listed below and their order of priority.</u>	Relative importance to SSI behavior.
2	Damping ratio distribution shape	Normal with Darendeli sigma truncation below $D = 0.1\%$	Lognormal with Darendeli-based Beta constrained to produce $D > 0.1\%$ at -2Beta	Two distribution shapes for damping with comparable variabilities and same lower bound. Other RVs by precedence and logic are modeled as lognormal.	Mean risk and distributions of foundation acc. and wall drift.*
3	Mean damping ratio at Low Strain	Values from BE model (based on GER report) Run 4E-4 AFE	Constrain BE $D_{\min} \geq 1\%$	BE D_{\min} ranges from 0.3% to 1.1% for all layers. Use 1% as a nominal in-field limit.	Same as 2.
4	V_s variability of GPS layer	Based on GER data	Divide Sigma by 1.4	Conservatively assume that variance could have been over-estimated by a factor of 2.	Same as 2.
5a	G/G_{\max} variability - all	Estimated variabilities from data	Divide Sigma by 1.4	Conservatively assume that variance could have been over-estimated by a factor of 2.	Same as 2.
5b	G/G_{\max} variability – selected layers and AFEs (TBD identified per importance from Qbt2, Qbt3 _u , -t, and GPS layers)	Estimated variabilities from data	Divide Sigma by 1.4	Conservatively assume that variance could have been over-estimated by a factor of 2.	Same as 2.
6a	Strength variability – Qbt4 and/or Qbt2 (TBD per importance)	Estimated variabilities from data and H-B model Run 4E-5 AFE	Divide Sigma by 1.4.	Conservatively assume that variance could have been over-estimated by a factor of 2.	Same as 2.
6b	Strength variability – transition layers	Estimated variabilities for rock layers above and below Run 4E-5 AFE	Use Sigma for Qbt3 _L	Use the lower variance of the adjoining layers as a lower bound	Same as 2.
6c	Strength variability – deeper layers	LHS factor equal to G_{\max} factor on stress. Run 4E-5 AFE	Use SQRT of LHS factor	Conservatively assume that variance in strength is half the variance in stiffness.	Same as 2.

* Review max. soil strain distributions at select locations if/where review in #1 indicates strong influence for the input RV.

Randomization and Sampling Questions (cont.)

Study ID	Subject	Base Case	Alt. Case(s)	Basis	Decision Factor
7	Distribution Truncation Questions	Previously completed analyses with 30 SSI models and one TH set and 2σ truncation	Similar simulation sets but <ul style="list-style-type: none"> • Truncate at 1.5σ • Do not truncate 	Examine distributions of resulting EDPs. Examine potential extreme values to determine if the underling SSI models are physically valid	Distributions of soil strains, foundation acc. and wall drift.

* Review max. soil strain distributions at select locations if/where review in #1 indicates strong influence for the input RV.

Accuracy and Robustness Questions

Study ID	Subject	Base Case	Alt. Case(s)	Basis	Decision Factor
For the following simulations, use N SSI models, M THs per AFE, and K pairings as determined previously u.n.o.					
1	Outlier simulations	P_f and risk including suspected outlier simulations	Repeat excluding suspected outlier simulations	Review response distributions to identify suspected outliers, e.g., extreme drift or soil strain.	P_f and risk.
2a	AFE range	Default AFEs + Lowest AFE at $P_f \leq 5\%$ and highest AFE at $P_f \geq 60\%$ or highest credible SSI response.	Lowest AFE at $P \leq 1\%$ Highest AFE at $P_f \geq 80\%$ or at $\sim 0.1 * \text{Mean risk}$	Scale input TH to the target AFE levels and use them to perform corresponding SSI analyses.	Mean risk.
2b	Extrapolation outside AFEs due to SSI model response credibility	Converged AFE limits from 2a	Use LB and UB P_f for AFEs beyond which SSI response credibility is questionable.	LB P_f can stay the same as the last AFE or use a lognormal fit, TBD. UB P_f TBD.	Mean risk.
3	Interpolation between AFEs	Original AFEs	Add SSI simulation at intermediate AFEs	Scale input TH to intermediate AFE levels. Compare risk from interpolated P_f values in each case. Add AFEs until accuracy is acceptable.	Mean risk.
4	Effect of SSI model variability relative to GM variability	"Full" LHS	BE SSI model + all THs	Separate effect of GM variability from all else.	Drift distributions and mean risk.
5	Effect of approximation in Qbt-4 discretization	Previously completed analyses with 30 SSI models and one TH set (uses Qbt-4-2 properties for Qbt-4 in the BE model)	Similar simulation sets but use Qbt-4-1 properties for Qbt-4 in the BE model	Examine distributions of resulting EDPs from this bounding analysis approach.	Distributions of soil strains, foundation acc. and wall drift.

Applicability and priority of which questions to quantitatively examine will depend on findings from previous questions.

Risk Process Questions

#	Subject	Question	Base Case(s)	Alt. Case(s)	How to Characterize
1a	Difference in effort between approaches	Required range and number of AFEs for wall drift limit-state	Use sensitivity results already generated	N.A.	Max. % change in P_f normalized by bin importance. Rate of mean risk convergence with range and no. of AFEs
1b	Difference in effort between approaches	Projected range of AFEs for all limit-states	SPRA from final LHS designs	<ul style="list-style-type: none"> SPRA with reduced wall drift capacity SPRA with increased wall drift capacity 	P_f values at current AFE limits AFE limits needed for P_f to have adequate coverage Estimated difference in mean risk
1c	Difference in effort between approaches	Required analysis effort	Use sensitivity results already generated	N.A.	Scope and complexity of TH development Required size of LHS Required number of explicit SSI analyses
2a	Difference in outcome between approaches	Difference in estimated risk	Mean risk from final LHS designs	N.A.	Difference in estimated mean risk using Approaches 2A and 2B Difference in GM bin contributions using both approaches
2b	Difference in outcome between approaches	Sensitivity to conditioning frequency	Mean risk from final LHS designs	NA.	Difference in estimated mean risk using Approach 2B @ two distinct conditioning frequencies vs. risk using Approach 2A
3a	Confidence in output	Sensitivity to fragility interpolation	Mean risk from final LHS designs (MLE P_f interpolation)	<ul style="list-style-type: none"> Multi-linear P_f interpolation Bounding P_f outside AFE range 	Difference in estimated mean risk per approach
3b	Confidence in output	Sensitivity to epistemic uncertainty	Mean risk from final LHS designs	<ul style="list-style-type: none"> Risk with reduced wall drift capacity Risk with increased wall drift uncertainty <p>Use assumed bias and higher variance in capacity as proxy for possible bias additional uncertainty in EDPs.</p>	Difference in estimated mean risk per approach vs. difference in mean risk between two approaches

Applicability and priority of which questions to quantitatively examine will depend on findings from previous questions.