New ASCE 4-Based Probabilistic Nonlinear SSI Analysis for Improving Seismic Fragility Computations

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Session VIII—Uncertainty in Soil-Structure Interaction (SSI) Analysis Invited Panel

10th Nuclear Plants Current Issues Symposium: Assuring Safety against Natural Hazards through Innovation & Cost Control
Charlotte, North Carolina, December 11-14, 2016
Purpose of This Presentation:

To show the application of the new ASCE 4-16 based probabilistic simulation-based SSI analysis recommendations (Chapters 2 and 5) can be applied to improve fragility calculations by presenting a case study of for a reinforced concrete shearwall building.

To answer key questions:

- How can be the new ASCE 4 recommendations on probabilistic SSI can be integrated for **beyond design-level** analyses within seismic fragility calculations? **PART 1** will respond to this.

- How the 2016 ASCE 4-based results differ from the 1994 EPRI-based results? **PART 2** will respond to this.

*2016 ACS SASSI V3 with Options PRO and NON was used.*
Introduction to New ASCE 4 Recommendations for Probabilistic Site Response and SSI Analysis
Based on the new ASCE 04-2016 recommendations for probabilistic seismic SSI analyses:

- Probabilistic SSI analyses should be performed using at least 30 LHS randomized simulations

- Probabilistic SSI responses should defined with the 80% non-exceedance probability level for the design-level applications.

- Probabilistic modeling should minimally include:
  - SEISMIC INPUT: GMRS/UHRS amplitude assumed to randomly varying (Methods 1 and 2).
  - SOIL PROFILE: Vs and D profiles (include spatial correlation)
  - STRUCTURE: Effective stiffness K and damping D as functions of the stress/strain levels in different parts of structure.
ASCE 4-16 Probabilistic SSI Simulation Concept

Stiffness

Damping

ACS SASSI V3 with Options PRO and NON

GRS Shape

Spatial correlation

Negative Correlation

2D Soil Profiles

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Probabilistic Seismic Input Models

ASCE 04-2015 Method 1

ASCE 04-2015 Method 2
Vs and D Soil Profile Probabilistic Models Using Multiple Segments Split

Different statistical properties for different soil profile segments in depth
Vs and D Soil Profile Probabilistic Models. Two Variation Scale Models Based on Field Data

Model 1 (Simple)  Model 2 (Composite)

(Popescu, 1996)

Short and large correlation lengths
Probabilistic Soil Material Curve Models

**G/Gmax-Shear Strain**

Soil curves show large correlation lengths along the shear strain axis.

**Damping-Shear Strain**
Probabilistic Structural Models. Effective Stiffness and Damping of Panels Are Dependent on Strain Level

- Keff and Deff variables should be defined by the user for each element group.
- Effective stiffness ratio Keff/Kelastic and damping ratio, Deff, are modeled as statistically dependent random variables. They can be considered negatively correlated, or Deff defined as a response function of Keff/Kelastic based on experimental tests.
Three major steps are applied:

1) **PREPARE SSI INPUTS:** Using ACS SASSI PRO modules, generate statistical ensembles for Probabilistic SRA and/or Probabilistic SSI analysis input simulations (*ProEQUAKE, ProSITE, ProSOIL and ProHOUSE, ProMOTION, ProSTRESS*).

2) **PERFORM SSI ANALYSIS:** Using ACS SASSI modules, run in batch the ensembles of the simulated input files to compute the SSI responses (*SITE, SITE, SOIL, HOUSE, ANALYS, MOTION, RELDISP, NONLINEAR, STRESS*).

3) **POST-PROCESS SSI RESPONSES:** Using ACS SASSI PRO module, post-process statistically the ensembles of the SSI responses (*ProSRSS, ProRESPONSE*).
PART 1:
ASCE 4 Probabilistic SSI Simulation-Based Fragility Analysis

Low-Rise Reinforced Concrete Shearwall Building Example
ASCE 4/43 Probabilistic SSI-Based Fragility Using Multiple Point Estimates (3-7 Review Levels)

- Probabilistic models for **SEISMIC** motion input for each review level are necessary. The UHRS input for each review level are necessary. Currently, 3 levels, 1e-4, 1e-5 and 1e-6 are considered. Deaggregate the bedrock UHRS in governing seismic events. Probabilistic models assume that the UHRS amplitude and frequency content have random variations.

- Probabilistic models for **SOIL** layer profiles for each review level are necessary. *Includes at least the Vs, D profiles and soil constitutive curves.* It should include the nonlinear soil behavior for each seismic motion simulation input.

- Probabilistic models for **STRUCTURE** material properties for each review level are necessary. *Includes effective stiffness and damping variations.* It should include the nonlinear structure behavior for each seismic motion simulation input.
Probabilistic SSI Performed Twice for Each Review Level for Random and Composite Variations

Two probabilistic SSI analysis input sets are required for PSA investigations:
1) All the randomness and the epistemic uncertainty variations to get the total variability \( (\beta_C) \)
2) All the randomness variations to get the randomness variability \( (\beta_R) \)

Compute epistemic uncertainty variability from Steps 1 and 2.
New ASCE 4 Probabilistic SSI Based Fragility Analysis for A Low-Rise RC Shearwall Building

Nuclear building model split in nonlinear panels; Done semi-automatically using ACS SASSI UI

Using ACS SASSI Option NON the effective stiffness and damping is automatically computed for each simulation

Wood 1990 Panel Shear Capacity, and Cheng-Mertz Hysteretic Model

Selected Panels
ACS SASSI Option NON Shearwall Hysteretic Models: Cheng-Mertz (CMB, CMS) and Takeda (TAK)
Useful References for Peak Capacity Equations:

• Barda et al., 1977 in the 1994 EPRI Reports – could overly estimate
• ASCE 43-05, 2005 Eqs. 4-3/4 based on Barda, ASCE 43-16 took out it
• ACI 349-06, 2006, Section 11.10, 21.4, based on Barda
• Wood, 1990 – small bias, typically less 10% lower, for median capacity
• Gulec and Whittaker, 2009, Eqs. 6.9-6.10, small bias for median capacity

NOTE: ATC 72-1 Option 3, 2010 for reduce yielding and peak capacities to account cyclic degradation effects for many cycles.
Shearwall Panel 17 Hysteretic Behavior
Barda (1977) vs. Wood (1990) for 0.60g Input
ARS at Different Elevations for Trans-Direction. Barda (1977) vs. Wood (1990) for 0.60g Input

Basemat

High-Elevation

AB ShearWall ARS (Node 570, Iteration 5) at Direction Y

Elastic
Wood 1990
Barda 1977

AB ShearWall ARS (Node 143, Iteration 5) at Direction Y

Elastic
Wood 1990
Barda 1977

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Including Wall Openings Semi Automatically

Solid Wall – 1 Panel

Wall with Two Openings – 3 Panels

Wall with Two Openings – 5 Panels

Shear Stress/Force

No opening (global wall failure)

With opening (local wall failure)

UI Commands: EDGE, 1,0,0,1, and then EDGE,2
Nonlinear SSI Effects Due Openings in Walls

Wood1990 Eq.
CMS Hysteretic Model

Panels 17 vs 42

0.25g
0.65g
Hazard Curve from PSHA Study - 7 Levels

0.25g GRS Simulations for Rock Site Using ASCE 4 Method 2

Horizontal

Spectral Amplitude

\[ \text{c.o.v.} = 28\% \]

\[ \text{c.l.} = 10\text{Hz} \]
Random Soil Profiles:
V1: Vs c.o.v. = 15% and c.l. = 1,000 ft
V2: Vs c.o.v. = 14% and c.l. = 100 ft
Total Vs c.o.v = 20%
Corr (Vs, D) = -0.40

Uncertain Scaling Factor:
Means = 1;
Vs c.o.v = 30%;
D c.o.v. = 40%;
Random BBC Input Variations for Nonlinear Walls

BBC Variations:
Mean = Wood 1990 shear capacity
Random: c.o.v. = 15%
Composite: c.o.v. = 33.5%
Wall Panel Hysteretic Behavior for 0.95g Level

Panel 17

Random

Panel 25

Composite
Compute uncertainty variable for each response simulation $j$, as $U_j = C_j/R_j$ for each quantity. Using the $U_j$ simulations compute the $U_{\text{mean}}$ and $U_{\text{c.o.v.}}$ for each response variable.
Computed 84% NEP Shear Strain and Pf/a in Walls

- 0.10g Level (Uncracked)
- 1.25g Level (Highly Nonlinear)

84% NEP Shear Strains For Random Variations

Ln R/S Reliability Model to Build Fragility Curve (Pf/a Data)

Computed Pf/a for a=0.95g Level
Fitting Lognormal Models for Fragility Curves

\[ \ln(a) = \ln(\bar{a}) + K_p \Phi^{-1}(P_f) \]

Linear Regression in Normal Space

Panel 17

\[ P_f(a) = \Phi\left(\frac{\ln(a/\bar{a})}{K_p}\right) \]

Fitted Lognormal Models

Panel 25
**Computation Overall Risk, Unconditional Pfail**

- Simulate Hazard Curves
- Simulate Fragility Curves
- Panel 25 Example
- Compute Simulated Total Risks
- Compute Overall Pfail Probability Distribution
## Levels ZPGA

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<th>ZPGA Level</th>
<th>ZPGA Value</th>
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<tr>
<td>3</td>
<td>1e-5 or 0.65g</td>
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### Pf for 7, 3 and 1 Level Seismic Hazard Levels

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### Random

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ARS for 5 Seismic Levels/2Hz Equipment Frequency

AB ShearWall (Random, Rock) -- ARS (Node 9) Direction X

- Mean(0.25g)
- 84% Prob(0.25g)
- Mean(0.45g)
- 84% Prob(0.45g)
- Mean(0.65g)
- 84% Prob(0.65g)
- Mean(0.95g)
- 84% Prob(0.95g)
- Mean(1.25g)
- 84% Prob(1.25g)

2Hz Band +/- 20%

N9 Higher Elevation
Up and then down

How good is Lognormal Model for Equipment Fragility Curves?

N576 Lower Elevation
Up, monotonic

2Hz Band +/- 20%
Lognormal Model for Fragility Curve Could Fail!

- **N9 Higher Elevation**
  - Up-down, Nonmonotonic FC

- **N576 Lower Elevation**
  - Up, monotonic FC

Lognormal CDF format for fragility curve breaks down!
Pf for N568 Y Using Point Data vs. Lognormal Fit

AB Shearwall Model (PF CDF) - Node 568 - Random at Frequency 2Hz - Direction Y - 10000 Samples

Point Data Fitting

Lognormal CDF Fitting

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ACS SASSI Framework Development

Present/Options A-AA, NON and PRO, Future/Options HAZ and FRAG

ACS SASSI Toolboxes

Future

On-going
PART 1 CONCLUSIONS

- ASCE 4-16 provides a probabilistic physics-based modelling for computing SSI response variations and fragility data, reducing substantially the traditional fragility model “expert” subjectivity…

- Traditional lognormal model for fragility curves appears to be often crude or even inappropriate on a case-by-case basis. This is especially true for the equipment fragility curves due to the ISRS resonant frequency shifting that is not captured by the simple lognormal probability model. Different fragility curve models should be used in future.

- The multiple level/multipoint estimate approach provides significantly different risk predictions than the traditional one level/point estimate approach with SSI response scaling. Using 1e-5 probability level with nonlinear SSI analysis as review level is better than using 1-e4 probability level with linear SSI analysis.
PART 2:
2016 ASCE 4 PSSI-Based Results vs. 1994 EPRI DSSI-Based Results

Low-Rise Reinforced Concrete Shearwall Building Example
The SSI analysis is performed for 5 SSI cases: BEstr-BEsoi, LBstr-BEsoi, UBstr-BEsoi, BEstr-LBsoi and BEstr-UBsoi.

The performance-based GMRS input is considered for seismic input. The ZPGA is 1g. For each SSI case, the Seismic input variability was considered by 5 sets of spectrum compatible acceleration histories based on “seed” records.

The 3 deterministic soil profiles, LB, BE and UB were obtained based on the 60 probabilistic nonlinear site response simulations assuming the UHRS inputs defined at bedrock (Vs > 9,200 fps).

The maximum SSI responses are computed for 15 Soil variability cases (5 inputs for each of the 3 cases BEstr-BEsoi, BEstr-LBsoi and BEstr-UBsoi) and 15 Structure variability cases (5 inputs for each of the 3 cases BEstr-BEsoi, LBstr-BEsoi and UBstr-BEsoi). Stiffness variations is elastic x 0.50 +/- 33%.

The SSI response median and variations are computed considering all the Seismic input, Soil and Structure variability cases. The total variation is based on the variations computed separately for Seismic, Soil and Structure variabilities.
ASCE 4 Probabilistic SSI-Based Methodology

Probabilistic Simulation vs. Deterministic GMRS (Method 2)

Probabilistic Simulation vs. Deterministic Vs Profiles (LB, BE, UB)

Target GRS
Mean of INPUT
Mean of Output
Output(84% Probability)
Output(16% Probability)
Samples(Outputs)
Probabilistic SSI vs. Deterministic SSI Results

Mean and 84% NEP Wall Panel Shear Strain

Panel 17

Panel 28
ASCE 4-Probabilistic SSI vs. EPRI-Deterministic SSI

EPRI vs. ASCE 4 Highest Risk Wall Panels

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Log. Std. Dev.
Probabilistic SSI vs. Deterministic SSI Responses

Comparative Structure Deformation at Same Time

**Deterministic SSI**
(BEsoi-LBstr)

**Probabilistic Nonlinear SSI**
(Simulation #26)

SEE ANIMATION
EPRI Deterministic SSI-Based 5 Analysis Cases

X-Direction

ARS at Node 482

Y-Direction

ARS at Node 568
ASCE 4 PSSI-Based ARS vs. EPRI DSSI-Based ARS

ARS at Node 482

Fragility at 2 Hz

X-Direction

Y-Direction

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ASCE 4 PSSI-Based ARS vs. EPRI DSSI-Based ARS

ARS at Node 568

X-Direction

Y-Direction

Fragility at 2 Hz

Fragility at 8 Hz
Include all input random variations

ARS at Node 9 Y-Direction

Fragility at 2Hz

Fragility at 8Hz

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## Comparative Fragility/Conditional Pf Estimates

### ISRS X-Dir Prob Failure Vector

<table>
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<tr>
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<th>2Hz ASCE</th>
<th>8Hz EPRI</th>
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### ISRS Y-Dir Prob Failure Vector

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PART 2 CONCLUSIONS

- The SSI structural behaviour is very different for ASCE 4 probabilistic nonlinear SSI simulations (nonlinear structure model) and the EPRI deterministic linear SSI simulations (linear cracked structure model with 0.5 median stiffness reduction and 7% damping). ASCE 4 PSSI modelling including nonlinear structure captures well the physical-behaviour including the shear deformation within structure.

- New ASCE 4 PSSI-based fragility results are quite different than the EPRI DSSI-based fragility results. Differences in the predicted risks/fragilities could be up to 1-2 order of magnitudes.

- The new ASCE 4-based probabilistic nonlinear SSI analysis provides a significant improvement of fragility calculations.