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Site-specific Adjustment Framework for IDA (SAF-IDA) for Regional Earthquake Damage and Loss Simulation

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ABSTRACT

In computational simulation of regional earthquake damage and loss, directly employing nonlinear time history analysis to estimate structural responses can be computationally intensive when the uncertainty of ground motion characteristics is considered. This paper proposes a new approach of using the site-specific adjustment framework for incremental dynamic analysis (SAF-IDA) to overcome this challenge. The SAF-IDA method can be used to train models for predicting structural response demands which can be then used in regional earthquake damage and loss simulation to enhance the computational efficiency. In the paper, the SAF-IDA method is introduced first. Then, discussions are made to integrate the SAF-IDA method into the earthquake simulation computational workflow developed by the Natural Hazards Engineering Research Infrastructure's Computational Modeling, and Simulation Center (NHERI SimCenter). Finally, a trial implementation is presented with preliminary results.

Introduction

Computational simulation of regional earthquake damage and loss is an essential component for quantitatively evaluating and scientifically mitigating the potential impacts from seismic hazard. The complexity of the problem is that a regional study usually encapsulates a broad spectrum of buildings, infrastructures systems, and facilities. Given the unique designs of important structures, e.g., tall buildings, explicitly simulating structural response would significantly improve the accuracy of predicted earthquake damage and loss, if compared to using intensity-based vulnerability functions. Although explicit simulations can be more time consuming in general, but they provide a higher resolution and direct link to structural design and retrofit. An important consideration in seismic response analysis is the characterization of earthquake ground motions based on the seismic hazard at the site where the structure is located. Given an earthquake scenario, the ground motion characteristics are still uncertain because of the variability of the earthquake source, wave propagation path, and site soil properties. This implies one major challenge in regional earthquake simulations: a high computational demand for sampling numbers of spatially correlated ground motions and conducting structural response analyses under the sampled ground motions.

This paper first briefs a new approach to overcome this challenge in regional earthquake damage and loss simulations

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by using the site-specific adjustment framework for incremental dynamic analysis (SAF-IDA) [1]. The SAF-IDA method is introduced first, followed by discussions to integrate the SAF-IDA model into the computational workflow for regional earthquake simulations developed by the Natural Hazards Engineering Research Infrastructure's Computational Modeling, and Simulation Center (NHERI SimCenter). Finally, preliminary results from a case study are presented.

Site-specific Adjustment Framework for IDA (SAF-IDA)

A recent study on Site-specific Adjustment Framework for IDA (SAF-IDA) proposed a new approach to efficiently estimate the site-specific probability distributions of structural performance metrics (*PM*), such as engineering demand parameters (*EDP*), damage measures (*DM*), or collapse capacity [1]. Fig. 1(a) shows the workflow of SAF-IDA and contrasts it with MSA. The SAF-IDA workflow involves three major steps: grid ground motion selection, IDA, and hazard consistent adjustment. Fig. 1(b) summarizes the procedure for selecting a grid ground motion set. The hazard consistent adjustment, as shown in Fig. 3(c), decomposes the $P(PM|Sa)$ to two parts: (1) the probability distribution of *PM* conditional on spectral accelerations, *Sa*, and supplemental ground motion parameters, IM_{suppl}, $P(PM|IM_{suppl},Sa)$, and (2) the site probability distribution of the supplemental parameters IM_{suppl} conditional on *Sa*, $f(IM_{suppl}|Sa)$. The $P(PM|Sa)$ is then computed by the conditional probability integral (Eq. 1).

$$P(PM|Sa) = \int P(PM|IM_{suppl}, Sa) f(IM_{suppl}|Sa) d(IM_{suppl}) \quad (1)$$

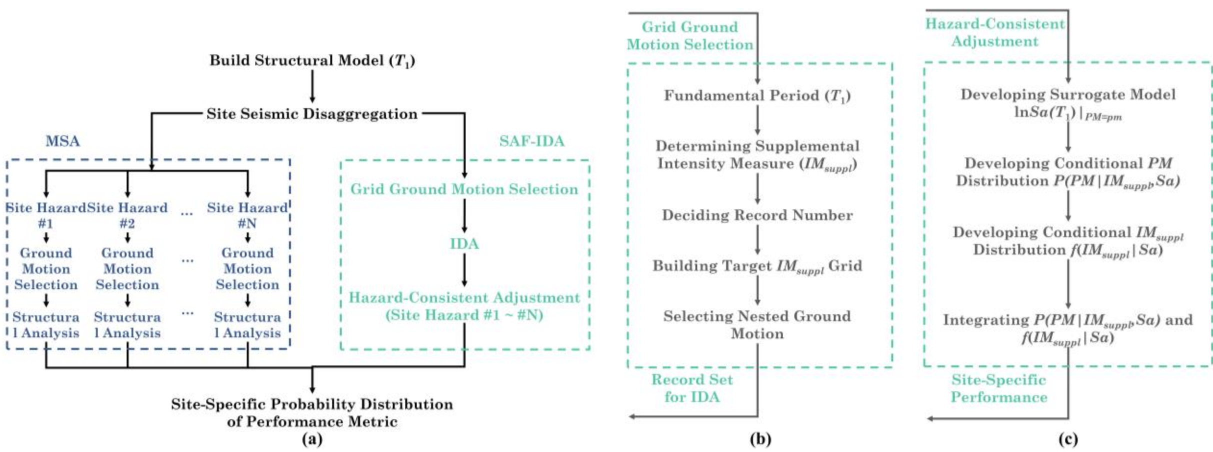

Figure 1. Flowcharts of MSA and SAF-IDA. (a) Workflows. (b) Grid ground motion selection. (c) Hazard consistent adjustment.

Grid Ground Motion Selection

A generic suite of ground motions is used in IDA to analyze the structure under incrementally increased ground motion intensities. For example, the FEMA P695 methodology [2] used 22 pairs of far-field ground motion records which were paired with 44 spectrally equivalent long-duration ground motions for studying earthquake duration effects on structural collapse safety [3]. In SAF-IDA, a grid ground motion selection algorithm is proposed to choose a suite of ground motions whose supplemental intensity measures are fit to a target grid, e.g., the grid with round points in Fig. 2(a) where the *SaRatio* [4] is a spectral shape measure as the ratio between $Sa(T_1)$ and average *Sa* over a range of periods (e.g., $0.2T_1$ to $3T_1$) and the $D_{S5\text{-}75}$ is the 5% to 75% significant duration measure [5].

The target grid can be designed to cover a sufficient combination of supplemental intensity measures that can influence structural responses. Once the target grid is configured, ground motions can be selected to minimize the distance between the target and selected points in the IM_{suppl} space. The rectangular dots in Fig. 2(a) show one example selected ground motion set (49 records). Fig. 2(b) plots the unscaled 5%-damped response spectra of selected motions against with the medina spectrum of the FEMA P695 far-field ground motion set. Two major advantages of using the grid ground motion set for IDA includes are (1) it can sample the ground motion characteristics more efficiently (i.e., less records to cover a wide domain) and (2) it can eliminate unintended correlations between different intensity measures of the selected ground motions.

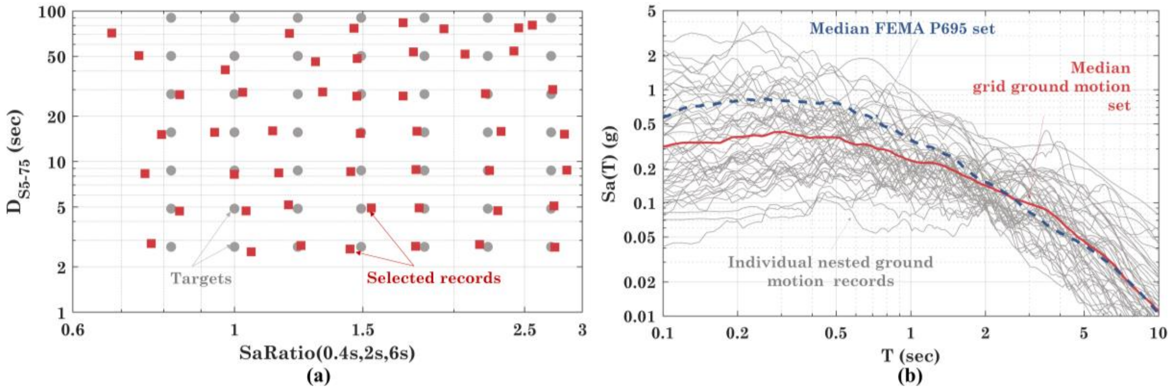

Figure 2. Example grid ground motion set, T_1 = 2*s*. (a) *SaRatio* and $D_{S5\text{-}75}$. (b) Individual and median unscaled response spectra.

Hazard Consistent Adjustment Procedure

The hazard consistent adjustment procedure includes three major steps: (1) estimating the probability distributions of performance metrics of the structure being evaluated conditional on the supplemental intensity measures and $Sa(T_1)$, i.e., $P(PM|IM_{suppl,}Sa)$ (e.g., Eq. 2 and Eq. 3), (2) computing the probability distributions of supplemental intensity measures for the site of the structure conditional on $Sa(T_1)$, i.e., $P(IM_{suppl}|Sa)$, and (3) integrating the $P(PM|IM_{suppl},Sa)$ with $P(IM_{suppl}|Sa)$ to compute the probability distributions of *PM* conditional on $Sa(T_1)$, i.e., $P(PM|Sa)$ (Eq. 4).

$$lnSa(T_1, PM = pm) = \ \widehat{c_0} + \widehat{c_1} lnSaRatio + \widehat{c_2} lnD_{S5-75} + \epsilon, \epsilon \sim N(0, \sigma^2) \quad (2)$$

$$P(PM \geq pm|Sa, SaRatio, D_{S5-75}) = \Phi\left(\frac{lnSa-(\widehat{c_0}+\widehat{c_1}lnSaRatio+\widehat{c_2}lnD_{S5-75})}{\sigma^2}\right) \quad (3)$$

$$P(PM|Sa) = 1 - \int P\big(PM \geq pm|IM_{suppl}, Sa\ \big)P\big(IM_{suppl}|Sa\big)d\big(IM_{suppl}\big) \quad (4)$$

Where Φ(·) is the cumulative distribution function of the standard Gaussian distribution. Fig. 3 provides example hazard-consistent adjustment for a 12-story concrete moment frame to illustrate the three steps. More detailed descriptions and validation studies were conducted [1].

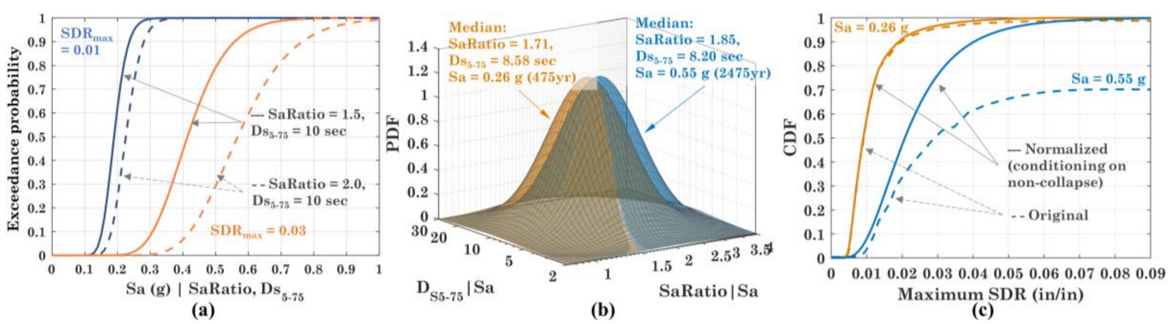

Figure 3. Illustration of hazard consistent adjustment. (a) $P(PM|IM_{suppl,}Sa)$. (b) $P(IM_{suppl}|Sa)$. (c) $P(PM|Sa)$.

Regional Earthquake Simulation Workflow

A computational application framework [6] is developed to leverage performance-based engineering to integrate interdisciplinary models and data to evaluate regional building damage and loss under earthquake and hurricane scenarios. Fig. 4 shows its basic concept where a regional analysis workflow can consist of multiple modules (i.e., puzzle pieces) addressing individual tasks, e.g., asset description, hazard characterization, asset modeling, response estimation, and damage-loss and recovery modeling. In a regional earthquake simulation, the response estimation module analyzes individual structures under site-specific ground motions to estimate interested engineering demand parameters (EDP). As previously discussed, for important structures with unique designs (e.g., tall buildings), this step usually involves numbers of nonlinear time history analysis. The number of analysis can increase rapidly if one considers the ground motion uncertainty or performs a time-dependent assessment which is even more computationally demanding.

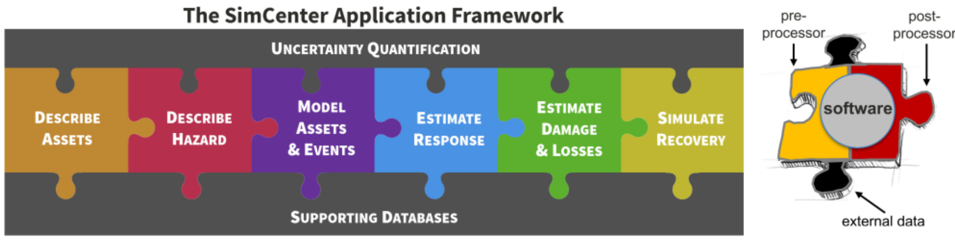

Figure 4. Modules of the software application framework developed by SimCenter (Deierlein et al., 2020).

Instead of running time history analysis, an alternative solution would be using the proposed SAF-IDA method to first train models that can predict interested EDPs given the site-specific ground motion characteristics and then using the trained model in the simulation workflow, which can significantly enhance the computational efficiency. The next section will introduce a trial implementation of this idea and discuss the preliminary results.

Trial Implementation and Case Study

An 8-story reinforced-concrete structure is used as the archetype structure whose IDA data is used to train the SAF-IDA model to predict the maximum story drift ration (SDR) and peak floor acceleration (PFA). The building is assumed to located at downtown San Francisco (Site Class B) and subjected to a 2475-year return period earthquake scenario, $Sa(T_1) = 0.3g$. The response spectra of selected 450 records are plotted in Fig. 5(a). The median significant duration $D_{S5\text{-}75}$ is about 14s. The structural model is built in OpenSees and analyzed under the selected 450 records on parallel via DesignSafe which took about 1350 CPU-hours to generate 7200 EDP data points. In comparison, same amount of data are predicted by the trained SAF-IDA model on a single CPU with about 20 minutes. Fig. 5(b) contrasts the estimated median and standard deviation EDPs. Both the direct simulation and SAF-IDA prediction are used for the damage and loss assessment using the *HAZUS MH EQ* method in pelicun [7]. Fig. 5(c) compares the estimated damage states based on two approaches.

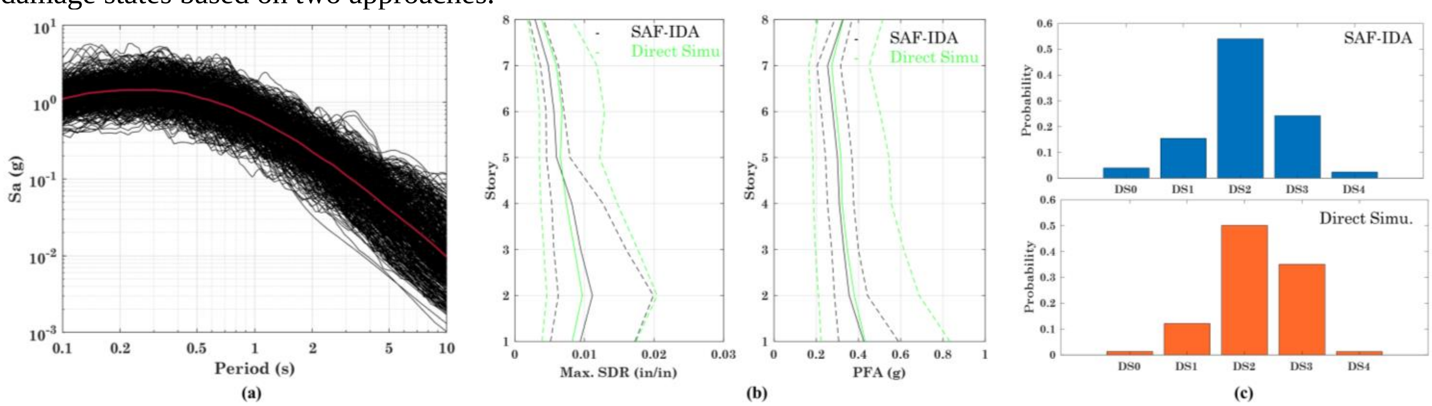

Figure 4. SAF-IDA vs. direct simulation results. (a) Ground motion records. (b) Maximum SDR and PFA demand distributions. (c) Probability of damage states.

Summary

In this paper, The SAF-IDA method is introduced and integrated with the earthquake simulation computational workflow developed by the Natural Hazards Engineering Research Infrastructure's Computational Modeling Simulation Center (NHERI SimCenter). The SAF-IDA method is used to train models for efficiently predicting the maximum SDR and PFA demand distributions of the example building under 450 records. The prediction is used for assessing the earthquake damage states which are found to be consistent with the estimates based on direct simulations. Future studies can be conducted to further validate and extend the proposed SAF-IDA method for three-dimensional models and more structural systems (e.g., with lower ductility, shorter periods).

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