12th National Conference
on Earthquake Engineering
Salt Lake City, Utah
27 June - 1 July 2022
Hosted by the Earthquake Engineering Research Institute

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 intensity 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 enhance overcome this challenge. The SAF-IDA method can be used to train models for predicting interested structural response demands which can be used in regional earthquake damage and loss simulation to enhance the computational efficiency. The SAF-IDA method will be introduced first. Then, discussions will be 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 needed to quantitatively evaluate and scientifically mitigate the potential impacts from seismic hazards. 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 increase the accuracy of estimates of earthquake damage and loss, if compared to using intensity-based vulnerability functions. Explicit structural response simulations can be more time consuming by developing and analyzing numerical models, but they provide a higher resolution and more direct link to structural design and/or retrofit. An important consideration in seismic response analyses of structures is characterization of the earthquake ground motions based on the seismic hazard at the site where the structure is located. The ground motion characteristics are uncertain resulted from the uncertainty in the earthquake source, wave propagation path, and site properties given an earthquake scenario. This implies one major challenge: a high computational demand for sampling a large number of spatially correlated ground motions and conducting structural response analyses under the sampled ground motions.

This paper first briefly introduces a new approach of using the site-specific adjustment framework for incremental

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Zhong K., Chandramohan R., Baker J. W., Deierlein G. G. Site-specific Adjustment Framework for IDA (SAF-IDA) for Regional Earthquake Damage and Loss Simulation. *Proceedings of the 12th National Conference in Earthquake Engineering*, Earthquake Engineering Research Institute, Salt Lake City, UT. 2022.

dynamic analysis (SAF-IDA) [1] to overcome this challenge in regional earthquake damage and loss simulations. First, the SAF-IDA method and model validation will be introduced. Then, discussions will be made 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 will be presented.

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

The prior studies (REF to be added) suggest IDA can be used for computationally-demanding seismic response analysis by appropriately designing the ground motion set and post-processing the IDA results. With this motivation, a recent development of Site-specific Adjustment Framework for IDA (SAF-IDA) can be used 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 general workflow for SAF-IDA and contrasts it with MSA. The SAF-IDA process involves three basic steps: grid ground motion selection, IDA, and hazard consistent adjustment. Fig. 1(b) summarizes the selection of 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 following conditional probability integral, evaluated over the full range of the vector of supplemental ground motion parameters (Eq. 1).

$$P(PM|Sa) = \int P\left(PM\middle|IM_{suppl}, Sa\right) f\left(IM_{suppl}\middle|Sa\right) d(IM_{suppl}) \tag{1}$$

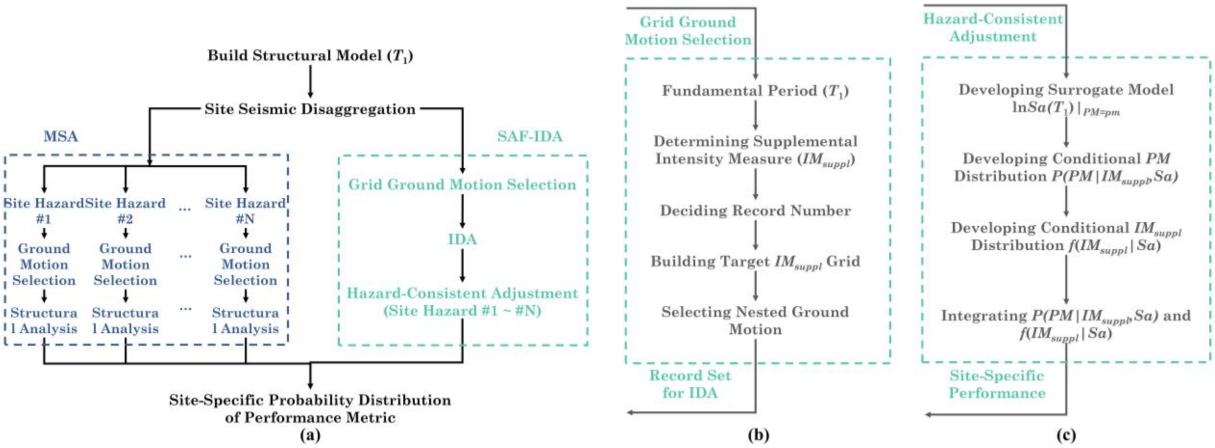

Figure 1. Flowcharts of MSA and SAF-IDA. (a) General workflows. (b) Grid ground motion selection. (c) Hazard consistent adjustment.

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] uses 22 pairs of far-field ground motion records, and paired the far-field record set with 44 spectrally equivalent long-duration ground motions [3]. While a grid ground motion selection algorithm is proposed for the SAF-IDA method 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 4% to 75% significant duration measure [5].

The target grid can be designed to cover a sufficient combination of supplemental intensity measures that are interested in. Once the target grid is set, ground motions can be selected to minimize the error between the distance between the target grid and selected points in the IM_{suppl} space. The rectangular dots in Fig. 2(a) shows 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 as a comparison. 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.

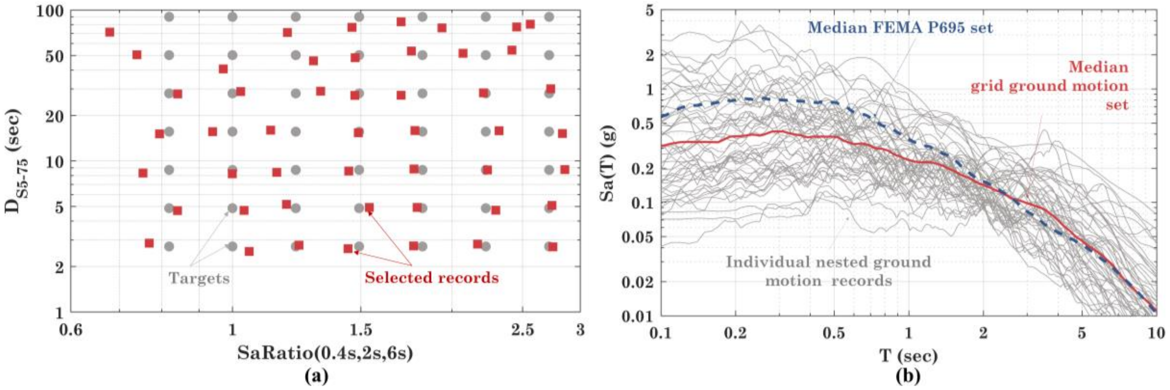

Figure 2. Example grid ground motion set, T_1 = 2s. (a) *SaRatio* and $D_{S5\text{-}75}$. (b) Individual and median unscaled response spectra.

Hazard Consistent Adjustment Procedure

The hazard consistent adjustment procedure of SAF-IDA 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 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).

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

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

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

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].

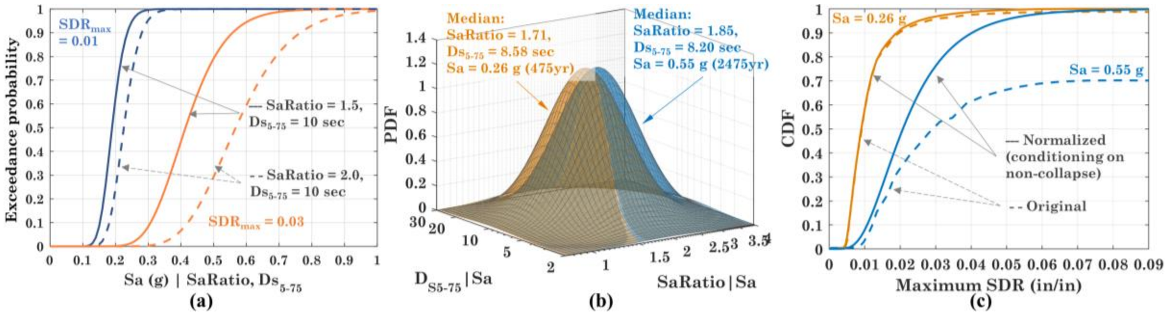

Figure 3. Illustration of hazard consistent adjustment. (a) $P(PM|IM_{suppl},Sa)$. (b) $P(IM_{suppl}|Sa)$. (c) $P(PM|Sa)$.

Regional Earthquake Simulation Workflow

An 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 consists of multiple modules (i.e., puzzle pieces) addressing individual tasks including asset description, hazard characterization, asset modeling, response estimation, and damage-loss and recovery modeling. In a regional earthquake simulation workflow, the response estimation module analyzes individual structures under site-specific ground motions to estimate response, i.e., engineering demand parameter (EDP). As previously discussed, for important structures with unique designs (e.g., tall buildings), this step usually involves nonlinear time history analyses. However, the number of analyses can increase rapidly if one would like to consider the ground motion uncertainty or conduct a time-dependent assessment, which makes the simulation computationally demanding.

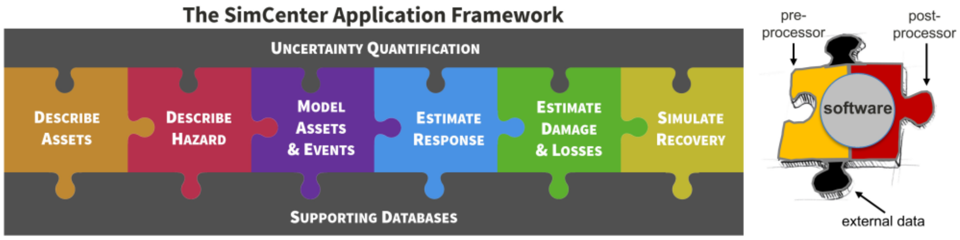

Figure 4. Modules of the software application framework developed by SimCenter (Deierlein et al., 2020).

Instead of running time history analyses online, an alternative solution would be to use the SAF-IDA method to train models that can predict interested EDPs given the site-specific ground motion characteristics and then use 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 from the case study.

Trial Implementation and Case Study

An 8-story reinforced-concrete structure is used as the archetype structure whose IDA data is used to pre-train the SAF-IDA model to predict the EDP demand. The building is assumed to located at downtown San Francisco (Site Class B) and the building is analyzed for a 2475-year return period earthquake scenario, $Sa(T_1) = 0.3g$. The response spectra of the 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 X hours with 450 CPUs. Including the eight peak story drift ratios and eight floor accelerations under 450 ground motions, 7200 EDP data points are also predicted by the pre-trained SAF-IDA model on a single CPU with about 20 minutes. Fig. 5(b) contrasts the estimated median and standard deviation of 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.

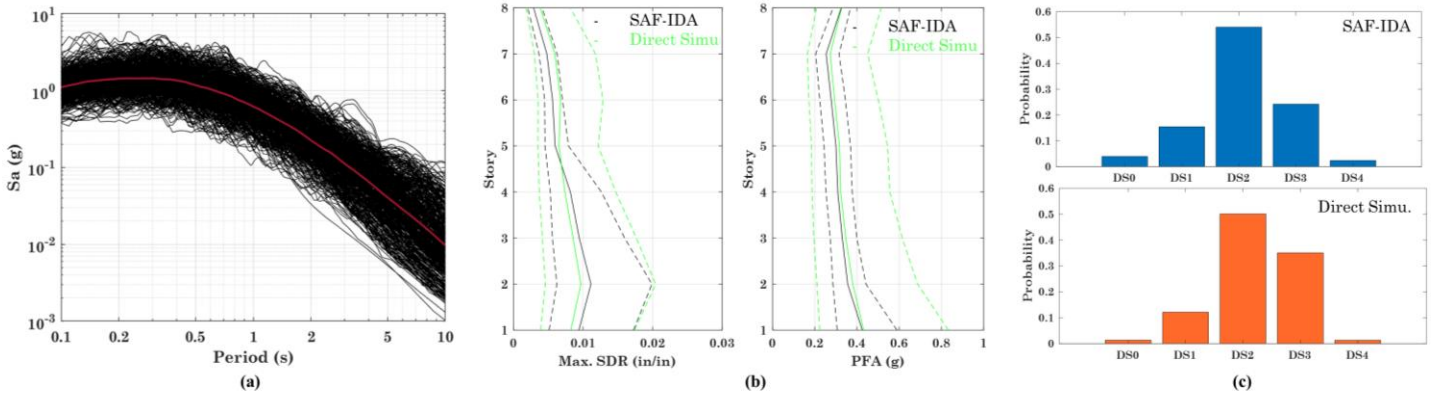

Figure 4. SAF-IDA vs. direct simulation results. (a) Ground motion records. (b) Maximum SDR and PFA demand distributions. (c) Probability of damage states.

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.

Acknowledgement

This work was supported by the Pacific Earthquake Engineering Research Center Transportation Systems Research Project (PEER-TRSP), the National Science Foundation (CMMI-1612843 and 2131111), and the Blume Earthquake Engineering Center at Stanford University.

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