Automated workflow for validation of ground motion simulations using conventional and complex intensity measures

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1. Introduction

Ground motion intensity measures (IMs) are widely used in Performance-Based Earthquake Engineering (PBEE) to quantify seismic hazard and potential demands on structures, examples include peak ground acceleration (PGA), spectral acceleration (SA), Arias Intensity (AI), significant duration (Ds), among others.

Because of their simplicity, IMs are a particularly useful set of summary statistics to examine ground motion severity. As a result, they have been common metrics by which to compare and validate ground motion simulation results relative to observational data.

The simplicity of conventional IMs is also their principal limitation in understanding the validity of simulated ground motions – because nonlinear seismic response of complex multi-degree-of-freedom structural and geotechnical systems are significantly more complex than any simple IM can describe. As a result, several studies have attempted to examine the seismic response of complex structural systems when subjected to small ensembles of simulated and observed ground motions (e.g. Galasso et al. 2012, 2013; Loghman et al. 2018).

In order to routinely compute complex seismic responses for simulated and observed ground motions we developed an extensible software framework that:

- **Plug-and-play:** New finite element models developed by others can be easily added to the set of systems considered. Simple interface scripts allow for a standardised communication between the independently-developed models, and the software workflow.
- **Computationally-efficient:** The workflow is optimised to consider multiple ground motion inputs in parallel, and also simple and advanced intensity measure calculations for a given ground motion input are also handled on separate computational resources.

2. Software architecture

Figure 1 illustrates the general software architecture that is used in the automated intensity measure workflow. The key features of the workflow are:

- **Simple IMs:** IMs such as PGA, PGV, etc, are trivial to compute from ground motion waveforms, and therefore Python scripts directly perform this task.
- **Advanced IMs:** Can be arbitrarily complex, therefore the most efficient approach is to provide a modular framework that can easily allow models developed by others to be inserted in a plug-and-play fashion into the workflow. This is achieved though a modular approach in which each complex model resides within a single directory and an interface script provides a simple API to enable common input/output. Examples for such interface scripts include how the three-component ground motion time series should be applied to the model and what outputs (displacements, forces etc) should be recorded as the 'advanced' IMs.

This is an open-source software project that provides engineering seismologists and structural/geotechnical earthquake engineers with an easy-to-use IM calculation and plotting capability, seen as a critical toolchain necessary to progress the comprehensive validation of ground motion simulation methods from the perspective of developers as well as users.

This software is open-sourced with MIT license, and freely available from GitHub. It is mostly written in Python 3, and partly written in Cython where more computational speed is desired.

Git repository: https://github.com/ucgmsim/IM_calculation

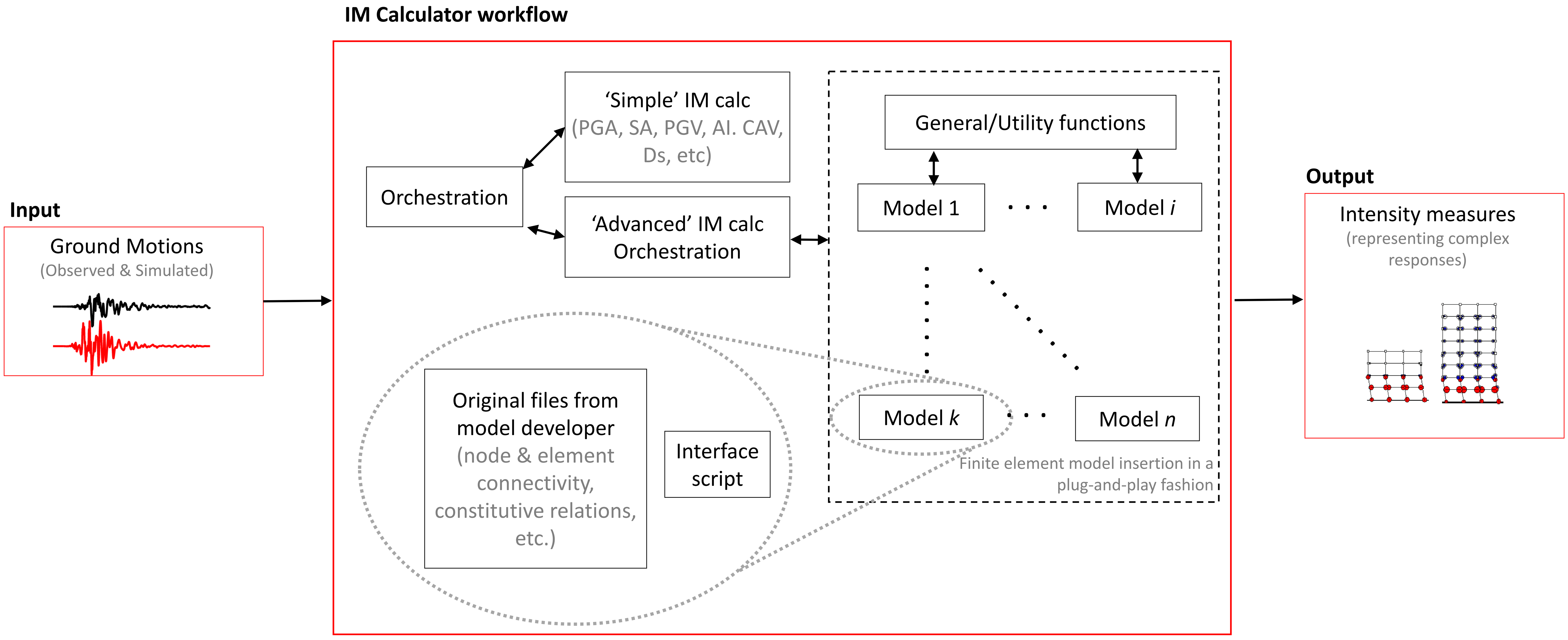

Figure 1: Schematic illustration of the Intensity Measure software workflow. Simple intensity measures are computed from the ground motion waveforms directly using Python scripts. 'Advanced' intensity measures are computed via an extensible modular framework which allows an easily plug-and-play insertion of new models developed by others.

3. Applications with simple intensity measures

Available simple IM metrics currently include peak ground acceleration (PGA), peak ground velocity (PGV), cumulative absolute velocity (CAV), Arias intensity (AI), duration (Ds575, Ds595), modified Mercalli intensity (MMI) and pseudo-spectral acceleration (SA) with a range of periods between 0.01 and 10.0 seconds.. Figure 2 provides an example illustration of the use of simple IMs for validation in the case of the 14 November 2016 Kaikōura earthquake

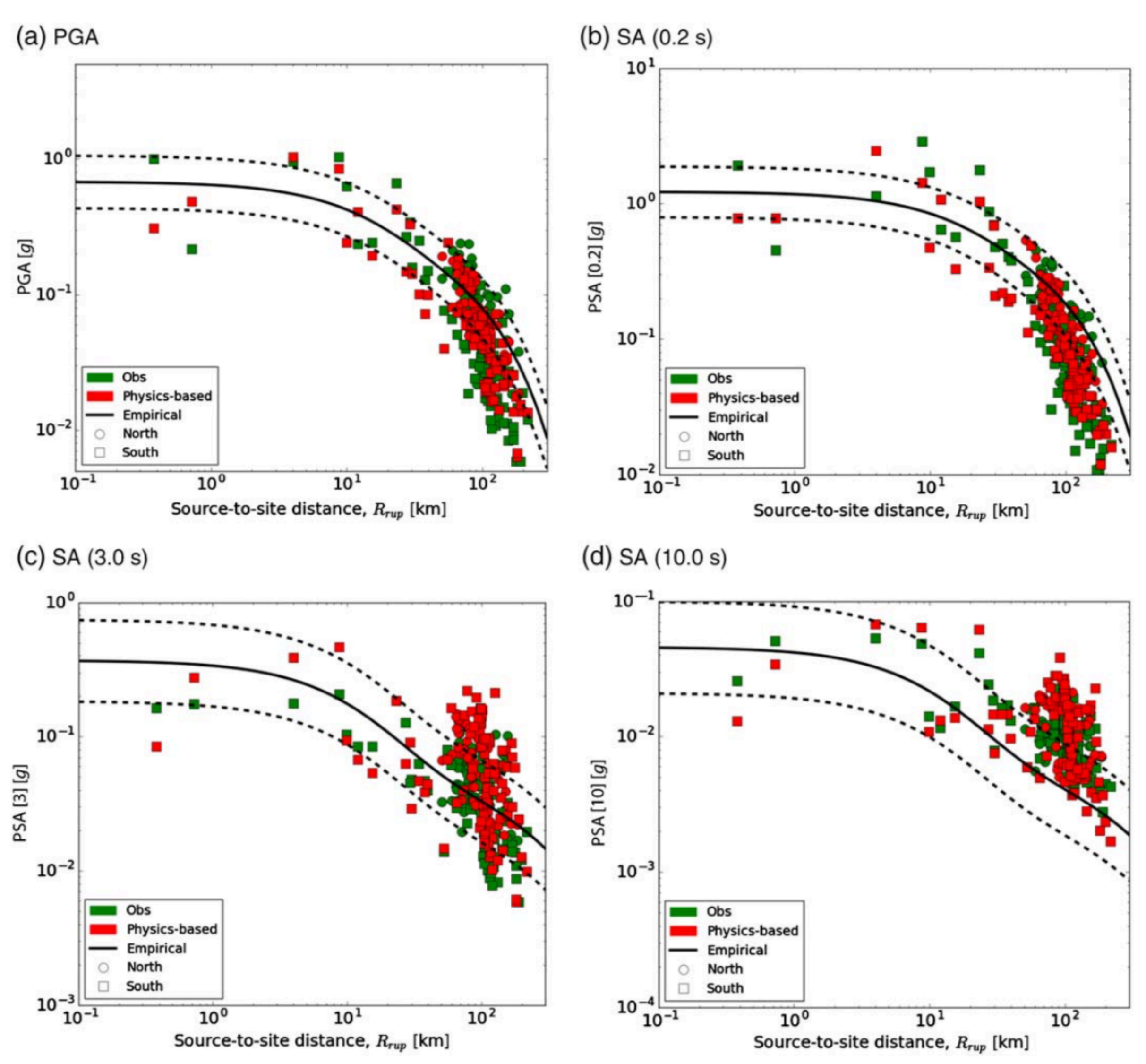

Figure 2: Comparison of observed and simulated ground motions from the 14 November 2016 Kaikōura earthquake in terms of response spectra at four vibration periods (after Bradley et al. 2017).

4. Applications with advanced intensity measures

Currently we have implemented two different finite element models developed by others using the open-source finite element software, OpenSees. Figure 3a illustrates on such model which is a nine storey SMRF building with a vibration period of T=2.95 seconds (see Loghman et al. 2019).

Figure 3b and 3c illustrate one output of the workflow in the form of advanced IMs representing the peak floor acceleration and inter-storey drift ratios throughout the building. The comparative responses between simulated and observed ground motions are quantified as a ratio of these computed responses – therefore a deviation from a ratio of 1.0 indicates a different response.

Because the development of complex structural response is non-trivial, then the utility of the developed software workflow is that it is easy to incrementally add more structural models and thus obtain a more comprehensive picture of the validity of ground motion simulations as viewed through the lens of complex structural or geotechnical responses.

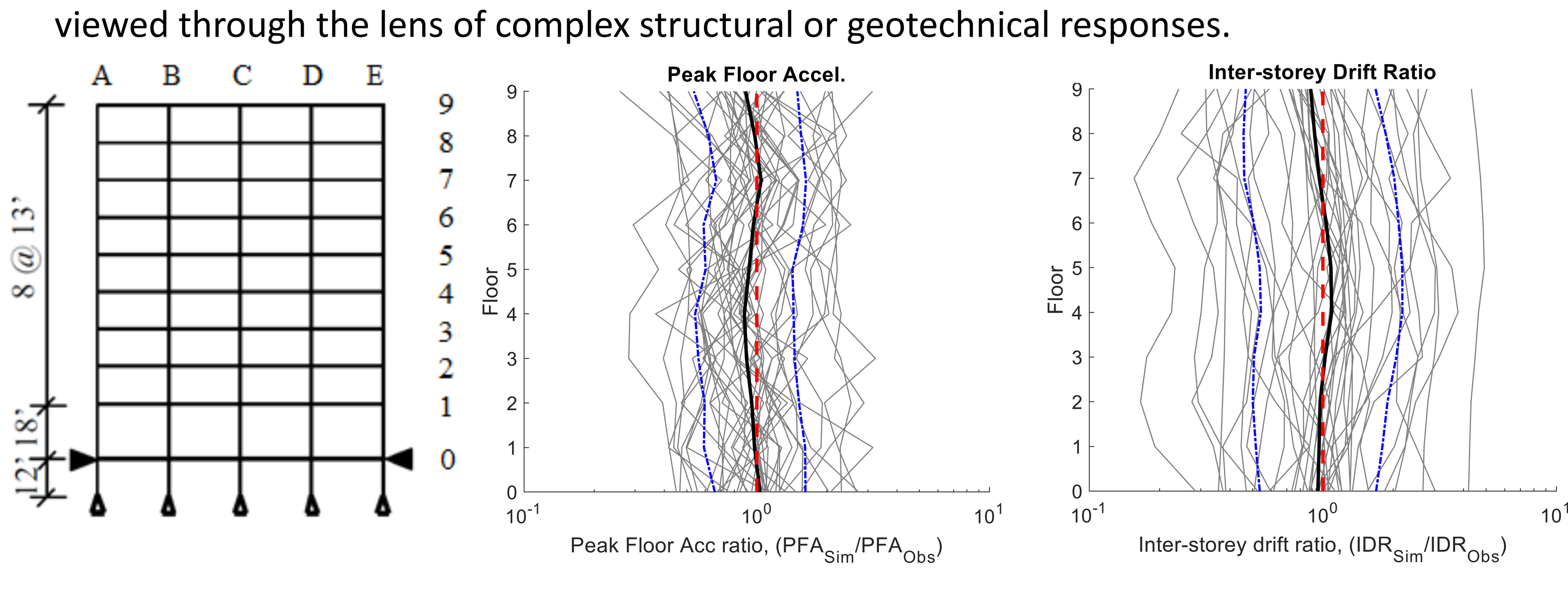

Figure 3: Comparison of observed and simulated ground motion pairs in terms of advanced IMs for a 9 storey structure (left) – peak floor acceleration (middle) and peak inter-storey drift ratio (right). Responses are expressed as a ratio between that computed using the simulated ground motion and that of the observed ground motion (after Loghman et al. 2019).