Validation of ground motion simulations using complex structural systems – New Zealand small magnitude events

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1. Motivation
Validation is an essential step in evaluating the applicability of simulated ground motions for utilization in engineering practice. It also provides valuable insights towards improving the simulation methodologies by highlighting specific limitations of simulation methods. Simulated ground motions can be validated with a range of model complexity, from a single degree of freedom through to complex 2D/3D systems. Although the use of simplified intensity measures, e.g. Sa(T), PGA, PGV..., for validation is common, it is unable to capture complexities of real engineered systems.

Objectives: The aim of this poster is to investigate the differences between the seismic response of two structural systems subjected to observed and simulated ground motions from small magnitude events across New Zealand via a novel analysis framework, which enables us to address the source of differences in responses of complex systems in terms of discrepancies in simplified intensity measures.

2. Ground Motions Considered
5349 pairs of unscaled simulated and observed ground motions from 498 small-magnitude events (3.5≤m≤5.5), across New Zealand (Figure 1) are used in this study. Considering the small magnitude events permits benchmarking the analysis framework for linear structural response. Simulations are conducted using the hybrid broadband method developed by Graves and Pitarka (2010, 2015).

Figure 1: a) 489 small-magnitude events, strong-motion stations, and observed ray paths; b) distributions of magnitude versus source-to-site distance; and c) source-to-site distance distribution.

3. Structural Systems Considered
Two steel special moment resisting frame buildings were selected for analysis (Figure 2). These buildings were designed for a site in Seattle based on US standards as part of the SAC Steel Project (FEMA 2000). Both structures are analysed subjected to all pairs of observed and simulated ground motions using OpenSees. Beams and columns are modeled as elastic elements with concentrated plastic hinges at their end (Figure 2b). Nevertheless, it is expected that the structures’ behaviour remains linear at this level of shaking. Inter-storey drift ratio is recorded as the structural response.

• Building A has three storeys, and the first five periods of vibration for this building are {0.98, 0.37, 0.17, 0.13, and 0.07} sec.
• Building B has nine storeys, and the first five periods of vibration for this building are {2.95, 1.08, 0.60, 0.38, and 0.27} sec.

4. Analysis Framework
To find the source of differences in engineering demand parameters (EDPs), it is logical to assume that they are primarily due to differences in simplified intensity measures (IMs). The analysis framework enables differences in the response of a complex system (AEVP) to be correlated to the differences in simplified IMs (∆IM) as well as remaining “unexplained” variability. Multivariate linear regression method is used to find which ∆IM contributes to the AEVP of interest (Equation 1).

\[ \text{AEVP} = a_0 \Delta IM_0 + a_1 \Delta IM_1 + \cdots + a_n \Delta IM_n \]  

This approach is graphically shown in Figure 3 for Building B inter-storey drift ratio (IDR), IM1 is considered EDP and IMs, the equation is written as:

\[ \Delta \text{IDR}_{\text{Building B}} = a_0 \Delta \text{Sa}(T_1) + a_1 \Delta \text{Sa}(T_2) + \cdots + a_n \Delta \text{Sa}(T_n) \]  

Figure 3: Comparison between the observed and simulated a) response spectra; b) structural response (IDR) along the height of 9-storey building.

5. Results
Results are shown for one example (IDR at the third storey, Building A) in Figure 4. First, the most correlated IM is selected as IM1 (herein Sa(T1), shown at Figure 4a). Figure 4b shows the relation between the ∆IDR and the IM1. The other IMs are selected based on the residual analysis. Figure 4c shows the relationship between the residual from the first step and the second IM. This procedure is continued while no dependency (p-value>0.05) between the residuals from the previous step and the candidate IM is captured (Figure 4d). The regression model using the Equation 2, for this example, can be written as:

\[ \Delta \text{IDR}_{\text{Building A}} = a_1 \Delta \text{Sa}(T_1) + a_2 \Delta \text{Sa}(0.33 s) - \xi \]  

Building A

Selected IMs: The selected variables following the above procedure are shown in Figures 5a, c for Building A and B IDR at each storey, respectively. The order of selected IMs is highlighted by different colours. As shown, the majority of the differences in IDR is explained by the difference of spectral acceleration at the main modes of vibration. As expected, the higher modes contribute more to the response of the taller building (Building B).

\[ R^2 \text{metric:} \]  

Figure 5: Selected variables contributing in ∆IDR and related coefficient of determination (R²) a-b) for Building A; c-d) for Building B along the height.

6. Conclusion
Simulated ground motions are typically validated by comparing simplified intensity measures (e.g., spectral acceleration (Sa)) with observed ground motions. However, validation based on simple intensity measures is unable to capture the complexities of engineered systems. This study aims to extend the validation procedure considering response of complex structural systems.

As a case study, the response of two structural models (a 3- and a 9-storey) were considered subjected to unscaled observed and simulated ground motions from small magnitude events across New Zealand. The results indicate that the high fraction of the difference between the observed and simulated responses can be explained by the difference of the spectral acceleration at the main modes of vibration contributing to the selected response, and at least 50% of cases can be explained via the selected intensity measures. This implies that the simulated ground motions which can capture the response spectra at the main modes of vibration can capture the response of structure well at the linear level. This study will extend to consider the moderate and large magnitude events to include nonlinear effects in the validation process.