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

Vahid Loghman, Brendon Bradley, Reagan Chandramohan, Robin Lee , Chris McGann

Department of Civil and Natural Resources Engineering, University of Canterbury

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 ($3.5 \le M_W \le 5$), 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).

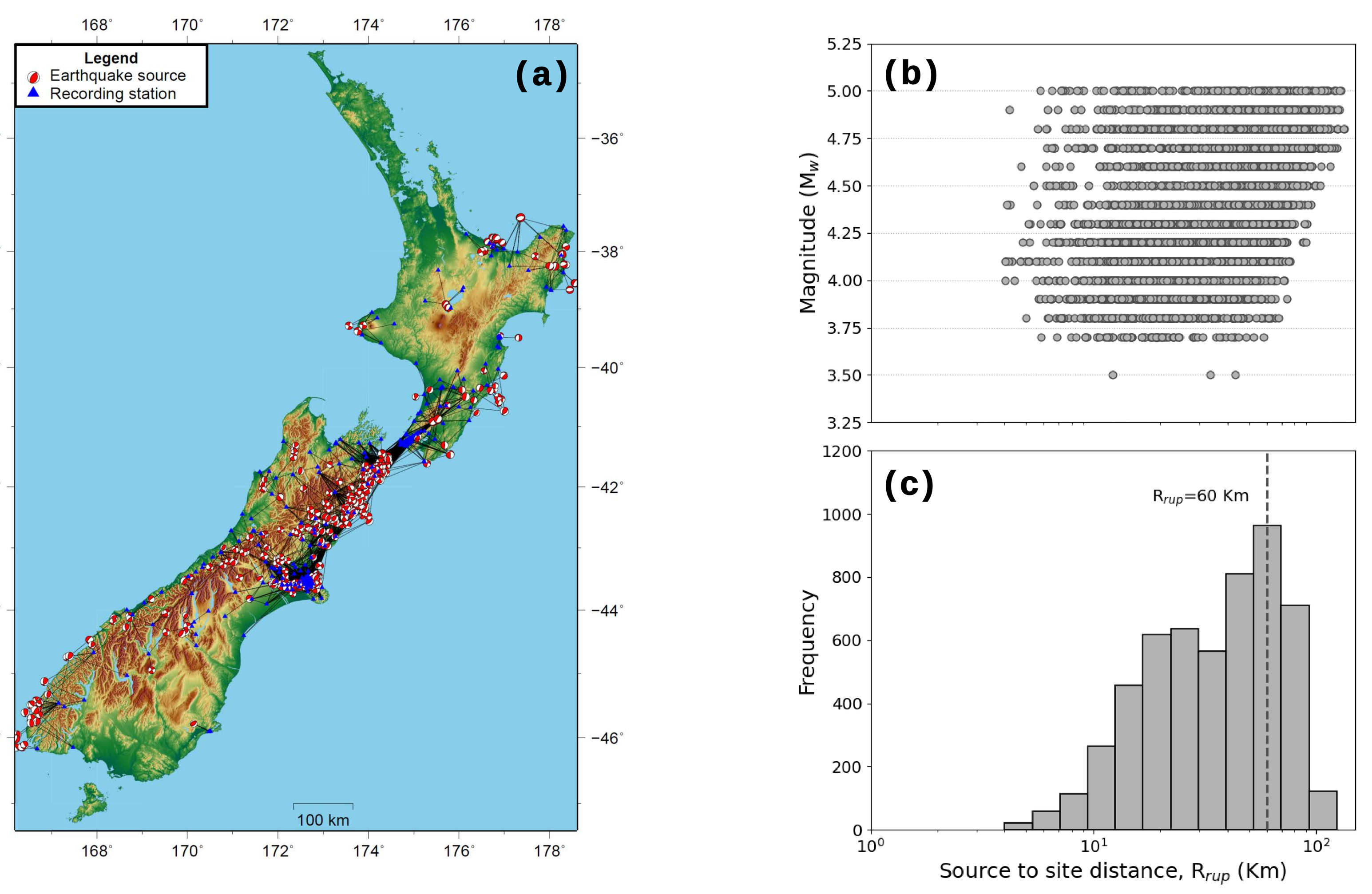

Figure 1: a) 489 small-magnitude events, strong-motion stations, and observed ray paths; b) distributions of magnitude versus source-to-site distance; and c) source-to-site distance distribution.

3. Structural Systems Considered

Two steel special moment resisting frame buildings were selected for analysis (Figure 2a). 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.

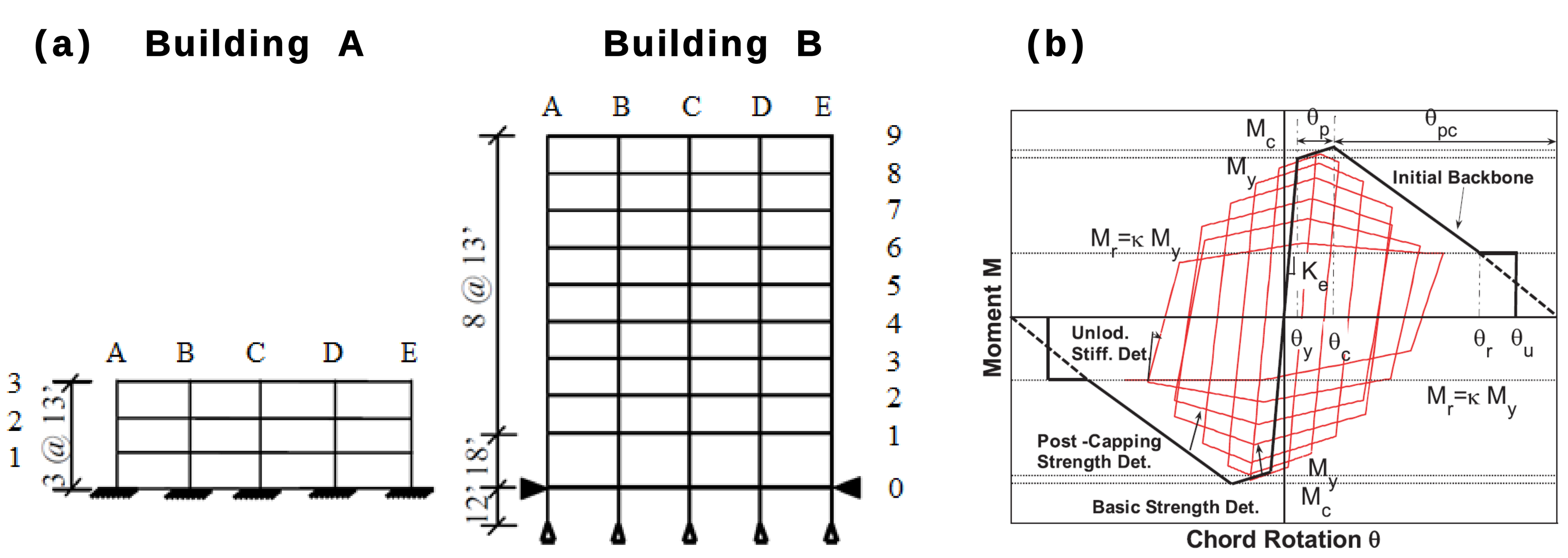

Figure 2: a) SAC steel frames (FEMA 2000); b) Hysteretic model of plastic hinges (Lignos et. al., 2011).

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 (ΔEDP) to be correlated to the differences in simplified IMs (ΔIM) as well as remaining "unexplained" variability. Multivariate linear regression method is used to find which ΔIM_i contributes to the ΔEDP of interest (Equation 1).

$$\Delta EDP \sim a_1 \Delta IM_1 + \cdots + a_n \Delta IM_n \quad (1)$$

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

$$\Delta IDR_{storey i} \sim a_i \Delta Sa(T_i) + \cdots + a_j \Delta Sa(T_j) \quad (2)$$

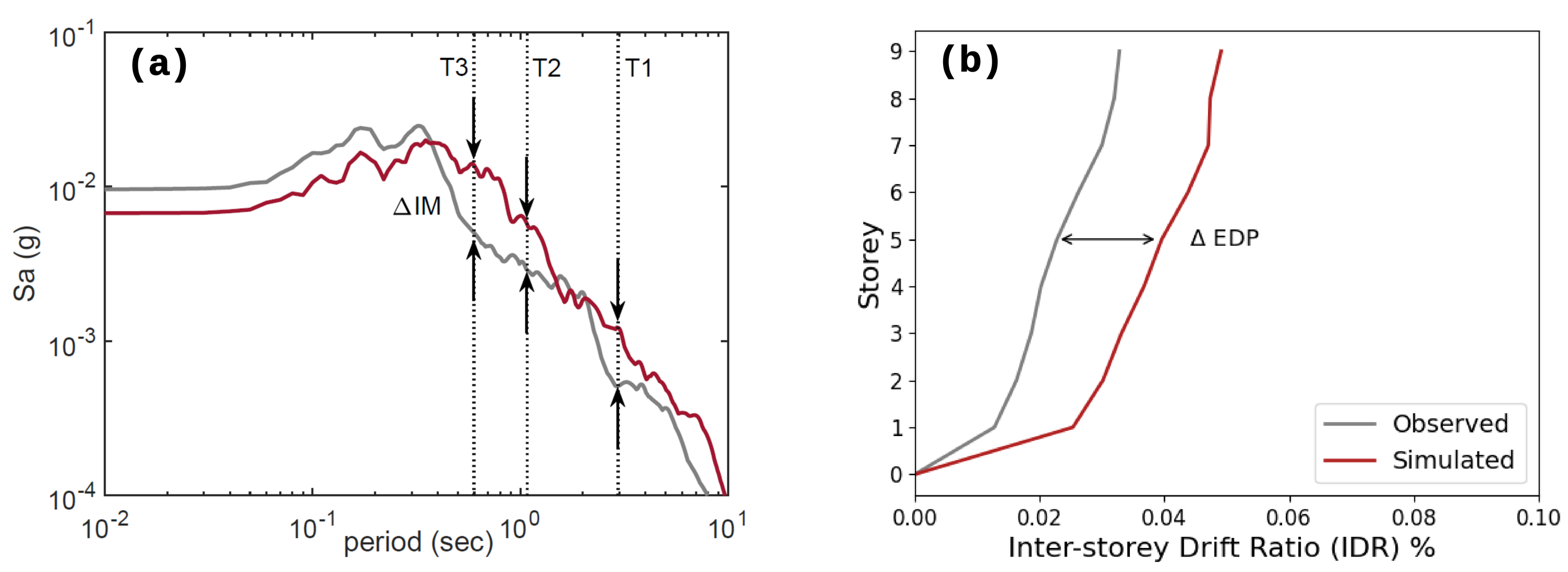

Figure 3: Comparison between the observed and simulated a) response spectra; b) structural response (IDR) along the height of 9-storey building.

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 IM_1 (herein $Sa(T_1)$, shown at Figure 4a). Figure 4b shows the relation between the ΔIDR and the IM_1. 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:

$$\Delta IDR_{storey3} = a_0 + a_1 \Delta Sa(1.0\ s) + a_2 \Delta Sa(0.33\ s) + \xi \quad (3)$$

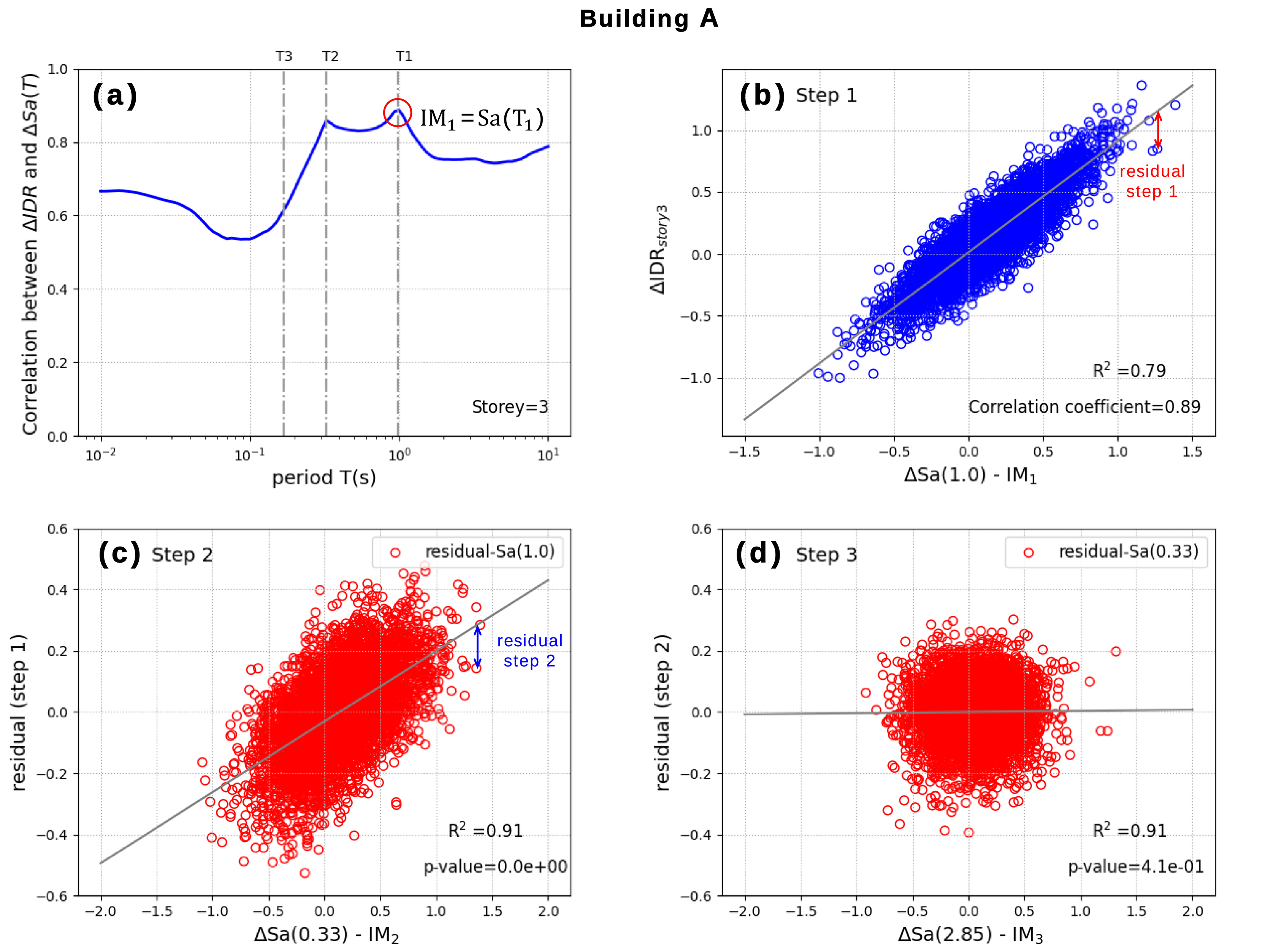

Figure 4: Variable selection procedure for IDR at the third storey a) Correlation between ΔIDR and $\Delta Sa(T_1)$; b) relation of ΔIM_1 with ΔIDR; c-d) relation of residuals with highest correlated ΔIM at steps 2 and 3.

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 metric: Figures 5b, d show how much of the differences in IDR are explained by the selected IMs. As shown, the higher fraction of differences can be explained by IM_1 (at least 75%). The explained part of model biases is increased by considering more IMs (~90%). However, the incremental improvement in the predictive capability of the regression model decreases with the addition of each subsequent IM (third IM and more).

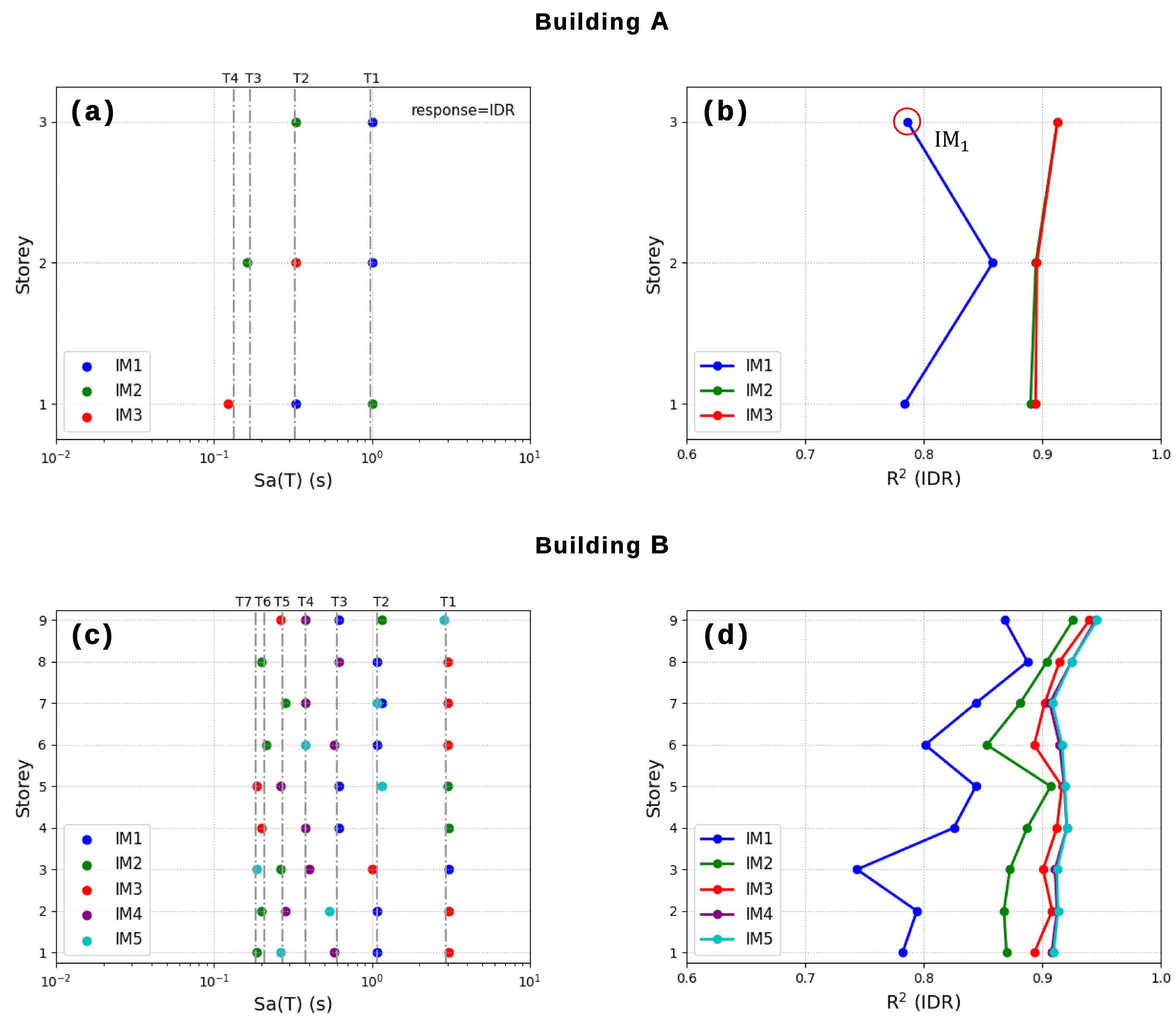

Figure 5: Selected variables contributing in ΔIDR and related coefficient of determination (R^2) a-b) for Building A; c-d) for Building B along the height.

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 90% of biases 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.