# MODEL VALIDATION OF RECENT GROUND MOTION PREDICTION RELATIONS FOR SHALLOW CRUSTAL EARTHQUAKES IN ACTIVE TECTONIC REGIONS

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## Introduction

- Recent earthquake ground motion prediction equations (GMPEs), such as those developed from the Next Generation Attenuation of Ground Motions (NGA) project in 2008, have established a new baseline for the estimation of ground motion parameters, such as peak ground acceleration (*PGA*) and spectral acceleration (*Sa*).
- When these relations were published, very little was written about model validation or prediction accuracy.
- We perform statistical goodness-of-fit analyses to compare the prediction accuracy of the ground motion prediction equations developed from the NGA project, and we present a model validation framework for assessing the prediction accuracy of GMPEs and aiding in their future development.

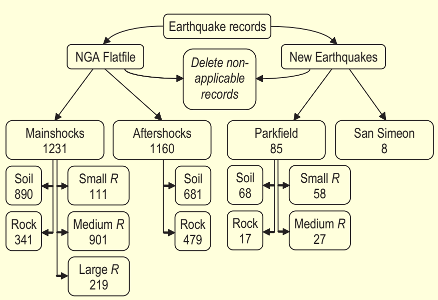
**GMPEs Explored in this study**

| NGA MODELS | | | PREVIOUS MODELS | | |
|---|---|---|---|---|---|
| *Developers* | *Abbr.* | *# of inputs* | *Developers* | *Abbr.* | *# of inputs* |
| Abrahamson and Silva | AS08 | 13 | Abrahamson and Silva | AS97 | 6 |
| Boore and Atkinson | BA08 | 5 | Boore, Joyner, and Fumal | BJF97 | 4 |
| Campbell and Bozorgnia | CB08 | 9 | Campbell | C97 | 5 |
| Chiou and Youngs | CY08 | 12 | Sadigh, Chang, Egan, Makdisi, and Youngs | SCE97 | 4 |
| Idriss | I08 | 3 | Idriss | I91 | 3 |

## Methodology

- Test models in two different ways:
  - On subsets of the NGA database used in model development
  - On data from recent California earthquakes not present in the databases used to develop the models (*blind comparison tests*)
- Compare the NGA relations with previous GMPEs on the blind comparison tests
  - 2004 *M* 6.0 Parkfield, California, earthquake
  - 2003 *M* 6.5 San Simeon, California, earthquake
- Compare the models' performance in various situations:
  - Mainshocks vs. aftershocks
  - Different distance ranges
    - Small ($R \le 10$ km)
    - Medium ($10 < R \le 100$ km)
    - Large ($100 < R \le 200$ km)
  - Different site conditions, separated by the average shear wave velocity over the top 30 m the subsurface ($V_{S30}$)
    - Soil ($180 \le V_{S30} < 450$ m/s)
    - Rock ($450 \le V_{S30} \le 1300$ m/s)

**Flowchart of the subset delineation process, with the number of ground motion records in each set ▸**




## Goodness-of-Fit Statistics

- The **Nash-Sutcliffe model efficiency coefficient (*E*)**, a commonly-used statistic in hydrology, is selected as the primary goodness-of-fit measure.
- The coefficient of efficiency:
  - Compares models to the ideal 1:1 line of Predicted = Observed
  - Assumes values from -∞ to 100%
  - Values less than 0 indicate that the arithmetic mean of the observed values has greater prediction accuracy than the model
  - More sensitive to differences between model predictions and observations than other typical goodness-of-fit measures (such as the correlation coefficient, *r*)
- The ground motion parameters tested are *PGA* and *Sa* at spectral periods of 0.1, 0.2, 0.3, 0.5, 1.0, and 2.0 sec.

$$E = \left[1 - \frac{\sum_{i=1}^{N}\left(Y_i - \hat{Y}_i\right)^2}{\sum_{i=1}^{N}\left(Y_i - \bar{Y}\right)^2}\right] \cdot 100\%$$

*where:*

$Y_i$ = observed value

$\hat{Y}_i$ = predicted value

$\bar{Y}$ = mean of observed values

$N$ = number of records

## Results

**Coefficients of efficiency, *E* (%)**

| | NGA MODELS | | | | PREVIOUS MODELS | | | |
|---|---|---|---|---|---|---|---|---|
| | AS08 | BA08 | CB08 | CY08 | AS97 | BJF97 | C97 | SCE97 |
| Mainshocks in NGA database | 54.8 | 58.1 | 59.3 | 42.7 | Previous models only tested in blind comparisons | | | |
| Aftershocks in NGA database | 47.9 | 47.6 | 41.2 | 43.1 | | | | |
| Parkfield dataset | 38.1 | 36.9 | 42.0 | 25.8 | 30.4 | 41.1 | 30.1 | 28.4 |
| San Simeon dataset | 66.2 | 67.0 | 66.2 | 70.3 | 55.5 | 58.8 | 49.2 | 34.0 |

- On the most comprehensive testing dataset (mainshocks in the NGA database), two of the simpler models (BA08 and CB08) outperform the more complicated AS08 and CY08 models.
- The NGA models' prediction accuracies are better for mainshocks than for aftershocks; AS08, CY08, and I08 included aftershocks in their regression databases, but BA08 and CB08 did not. One of each team's most significant model development decisions was whether to include aftershocks in their regression databases.
- The GMPEs perform best at intermediate distances, where most ground motion data are available.
- The Parkfield earthquake generated an unprecedented amount of near-source ground motion records; however, because near-source ground motions tend to be highly variable, the models have a relatively low prediction accuracy for this earthquake.
- The prediction accuracy of the models is much better for the San Simeon earthquake than for Parkfield, because highly variable near-source ground motions no longer dominate the database.

**Model rankings based on *E***

| | NGA MODELS | | | | PREVIOUS MODELS | | | |
|---|---|---|---|---|---|---|---|---|
| | AS08 | BA08 | CB08 | CY08 | AS97 | BJF97 | C97 | SCE97 |
| Mainshocks in NGA database | 3 | 2 | 1 | 4 | Previous models only tested in blind comparisons | | | |
| Aftershocks in NGA database | 1 | 2 | 4 | 3 | | | | |
| Parkfield dataset | 3 | 4 | 1 | 8 | 5 | 2 | 6 | 7 |
| San Simeon dataset | 3 | 2 | 3 | 1 | 6 | 5 | 7 | 8 |

## Discussion

### Incorporation of Aftershocks in Model Development

- The aftershock records of the 1999 *M* 7.6 Chi-Chi, Taiwan, earthquake comprise 83% of the aftershock records in the master NGA database.
- For the models that included aftershocks in their regression datasets, one potential problem with including such a high proportion of records from a single event is that the model may become over-fit toward the characteristics of that event, and the model's ability to generalize to other situations is lowered.

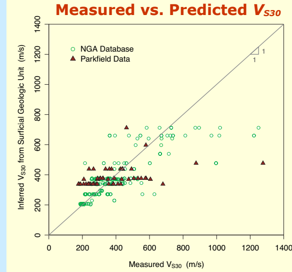
### Effect of Distance on Prediction Accuracy

- The CY08 model performs superiorly in the blind comparison tests at medium distances, but performs poorly in some other subsets.
- One of the key differences between CY08 and the other NGA models is that the CY08 regression dataset only included sites with $R \le 70$ km, while the other NGA teams included sites with $R \le 200$ km. Perhaps the over-fitting of the CY08 model to intermediate distances gives it increased predictive capabilities within that range, and decreased predictive capabilities outside of that range.

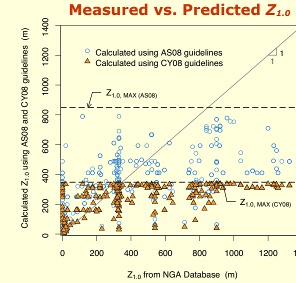
### Uncertainty of Site Parameters

- Of the model parameters, the greatest contribution to epistemic uncertainty comes from the site parameters. One of the major problems of shear wave velocity data is that actual measurements are sparse, and that guidelines for inferring site parameters at unsampled locations often lead to widely variable results.
- As seen below, there is excessive scatter in plots of predicted versus measured values for two site parameters used in the NGA relations: (1) $V_{S30}$; and (2) $Z_{1.0}$, the depth to $V_S$ = 1.0 km/s.

**Measured vs. Predicted $V_{S30}$**




**Measured vs. Predicted $Z_{1.0}$**




- The quantitative incorporation of site parameters in GMPEs is a step in the right direction, but a greater emphasis on site-specific data measurements would increase their prediction accuracies.

## Conclusions

- Increased model complexity does not necessarily lead to increased prediction accuracy.
- Creation of a regression database with large numbers of ground motion records with the same characteristics (whether from the same event or from within the same distance range) may cause a model to be over-fit towards those particular characteristics.
- A higher-quality regression dataset, with greater measurements of site characteristics, coupled with simple functional forms for the GMPEs, may yield the best solution.
- Proper sharing of modeling information for future GMPEs will aid users in correctly understanding and implementing these models in the next generation of seismic hazard analyses.

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