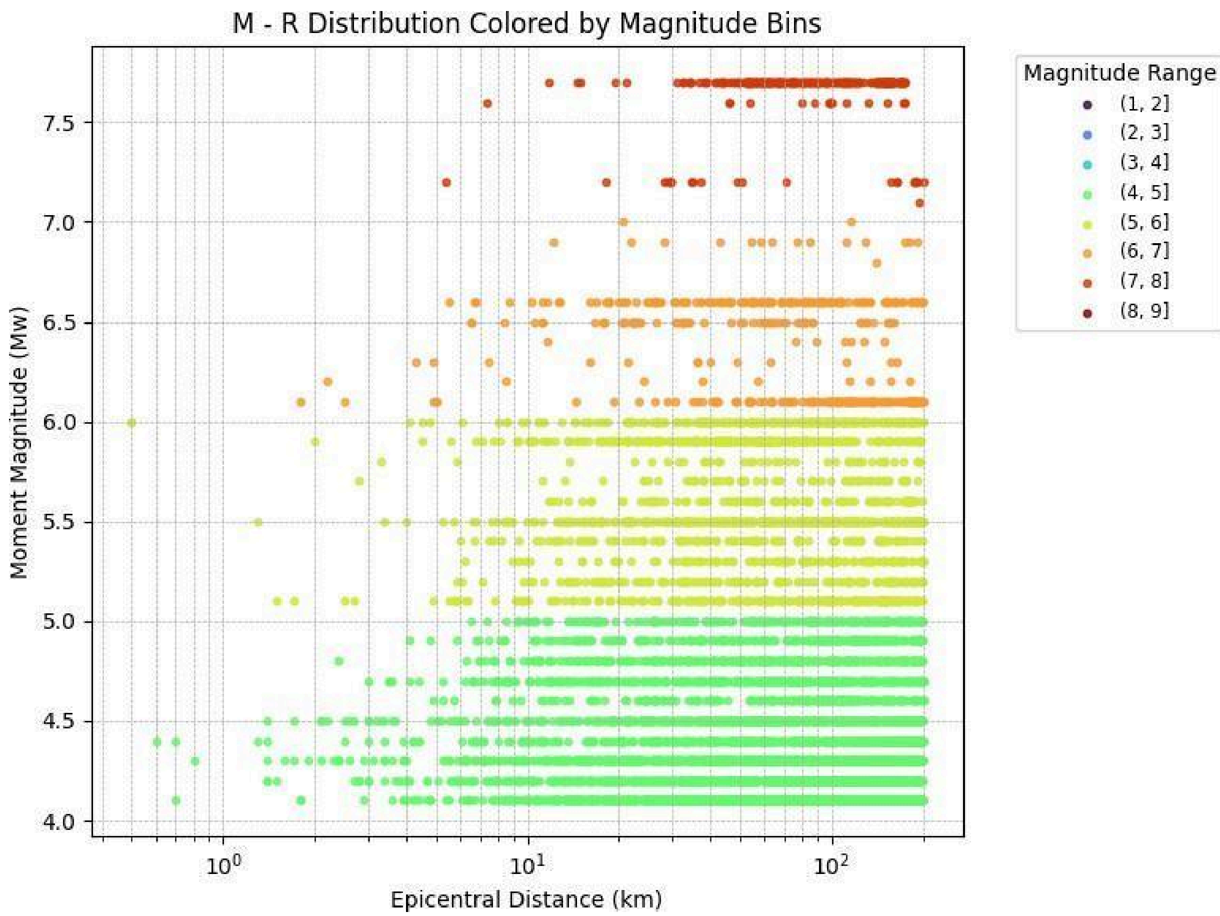
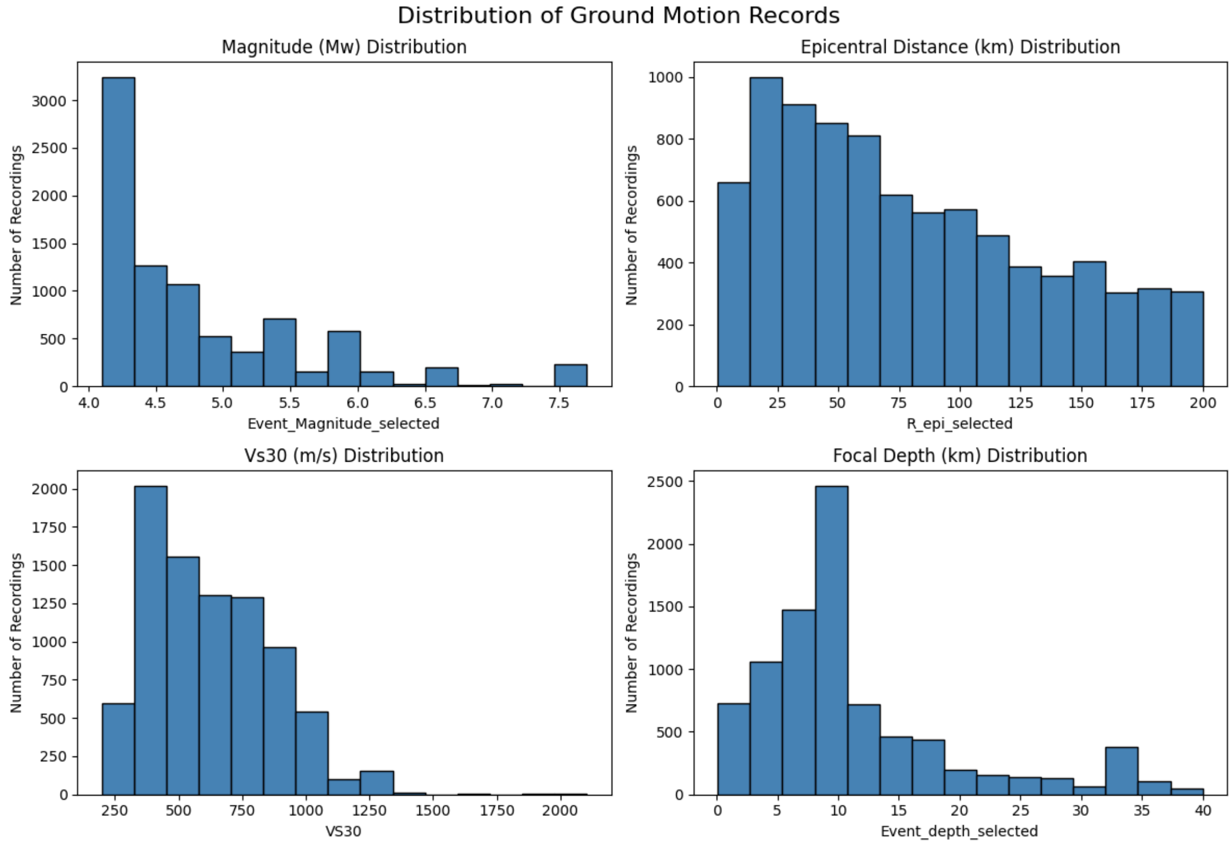
CGAN (Conditional Generative Adversarial Network)

1. **Magnitude vs Joyner-Boore Distance**



- Earthquake magnitudes in the dataset range from about 4 to 8 Mw, with a higher concentration of events between magnitudes 4 and 7.
- There is no clear trend or correlation between magnitude and R epi distance; earthquakes of all magnitudes occur across the full range of distances up to 1000 km.
- The data points are densely clustered at higher R epi distances (100 - 1000 km), indicating most recorded events are relatively away to the reference point, but significant events are also observed at closer distances.

2. Histogram of each input parameter



- **Magnitude (Mw):**

Most earthquake records have magnitudes between 4.0 and 5.0, with a sharp peak around 4 Mw. There are fewer records for both lower (>6.5) and higher (>7.5) magnitudes, indicating the dataset is dominated by slight to moderate earthquakes.

- **R epi distance:**

The majority of records are at distances between 25 km and 75 km, peaking near 20 km. The number of records decreases steadily at larger distances, showing that most recordings are made relatively close to the earthquake source.

- **Shear Velocity (VS30):**

Most records correspond to sites with VS30 values between 200 m/s and 600 m/s, peaking around 400 m/s. This suggests that the data predominantly represent sites with soft to moderately stiff soil conditions, with fewer records from very stiff or rock sites (VS30 > 800 m/s).

3. Table1

Table 01 - Input Parameters:

	Event_Magnitude_selected	R_epi_selected	VS30
min	4.1000	0.5000	198.0000
max	7.7000	199.9000	2104.2000
mean	4.8315	79.5987	623.9816
std	0.8117	53.8051	242.8279
skewness	1.5924	0.5351	0.6112
kurtosis	2.4603	-0.8112	0.0107

	Event_depth_selected
min	0.1000
max	40.0000
mean	11.1482
std	8.2397
skewness	1.5129
kurtosis	1.7629

Table 01 - Output Parameters:

	U_target_selected_1	U_target_selected_2	U_target_selected_3
min	0.0000	0.0000	0.0000
max	4836.5170	4302.4922	3097.6693
mean	10.0283	25.3087	30.2395
std	93.1098	162.5251	154.4057
skewness	24.2859	12.0879	9.2424
kurtosis	974.0350	185.9719	108.9522

	U_target_selected_4	U_target_selected_5	U_target_selected_6
min	0.0000	0.0001	0.0002
max	4299.3010	4713.7618	4196.1082
mean	32.3795	36.3600	37.8630
std	162.0937	175.5214	171.9430
skewness	11.3707	10.8141	10.1882
kurtosis	196.7534	180.0279	151.6814

	U_target_selected_7	U_target_selected_8	U_target_selected_9
min	0.0003	0.0004	0.0006
max	4130.3150	6415.0268	6400.9357
mean	40.1494	42.6016	45.3880
std	172.5549	188.0650	200.8263
skewness	8.3731	11.1739	12.4133
kurtosis	97.7752	218.8951	271.2209

Input Parameters:

- The input variables (mw, r_epi, vs30, depth) show a range of values, with means and standard deviations indicating moderate spread.
- Skewness and kurtosis values suggest that most input parameters are moderately skewed (either positive or negative) and have distributions close to normal.

Output Parameters:

- All output parameters have minimum values of 0 or close, indicating possible zero or censored data.
- The means are generally low compared to their maximums, suggesting that most data points are clustered near the lower end of the range.
- High skewness and kurtosis values across almost all output parameters indicate highly skewed distributions with heavy tails. For example, U_target_selected_8 has skewness of 11.79 and kurtosis of 218.19, showing extreme outliers or rare large values.
- Standard deviations are often close to or larger than the mean, reinforcing the presence of outliers or a wide range of values.

4. CGAN

1. Generator

- **Input:** Noise conditioned on input features (e.g., earthquake parameters like magnitude, distance).
- **Layers:**
    - Dense(128) with ELU activation → BatchNormalization
    - Dense(64) with ELU activation
    - Dense(output_dim) → No activation (direct output of PSA predictions)
- **Output:** Synthetic ground motion (e.g., predicted PSA values)

2. Discriminator

- **Input:** Concatenated [Input Features, Ground Motion Values] (either real or generated)
- **Layers:**

    - Dense(64) with ELU activation → Dropout(0.3)
    - Dense(32) with ELU activation
    - Dense(1) with **Sigmoid** activation (real/fake probability)
- **Output:** Probability that the input is real (vs. generated)

Loss Functions

Discriminator Loss:

- **Binary Crossentropy (BCE)** comparing:
    - Real samples → 1
    - Fake (generated) samples → 0

Generator Loss:

- **Adversarial Loss:** BCE (wants Discriminator to classify outputs as real → 1)
- **Reconstruction Loss:** MSE between generated PSA and true PSA
- **Total Loss = BCE + MSE**

Training Loop

- **Epoch-wise training** using batches from the training set
- **Early stopping** if R^2 exceeds 0.86 and generator loss < 5
- **Best weights saved** using validation set R^2 performance

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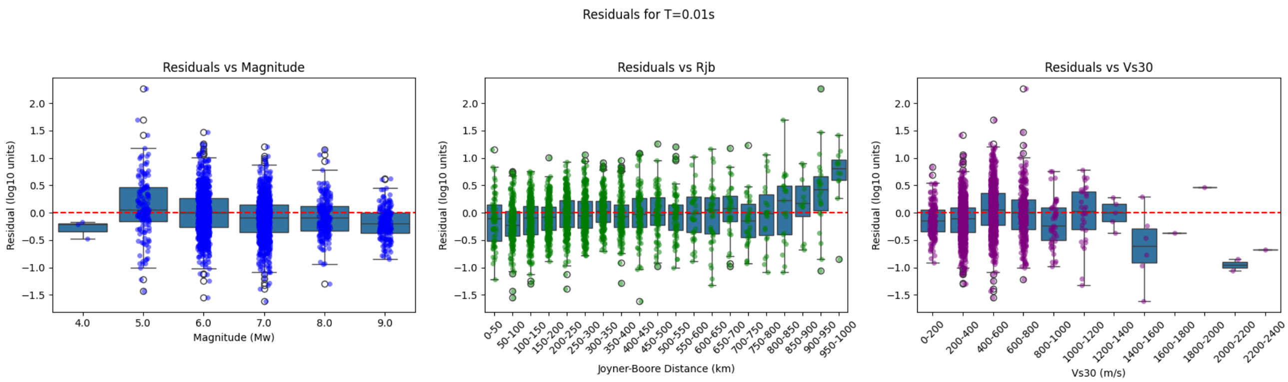
Evaluation Metrics

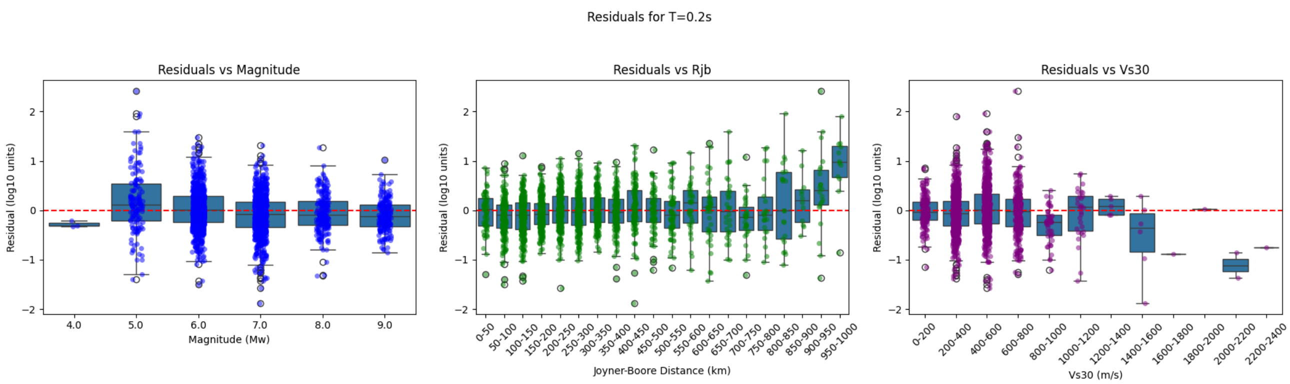
1. **Correlation Coefficients (R):** Pearson correlation for each output dimension
2. **Performance Parameter (PP):** Inverse MSE normalized by ground motion variability
3. **Slope (k):** Linearity of prediction vs. true values
4. **R^2 Score:** Explained variance
5. Absolute error from perfect R^2 (= 1.0)

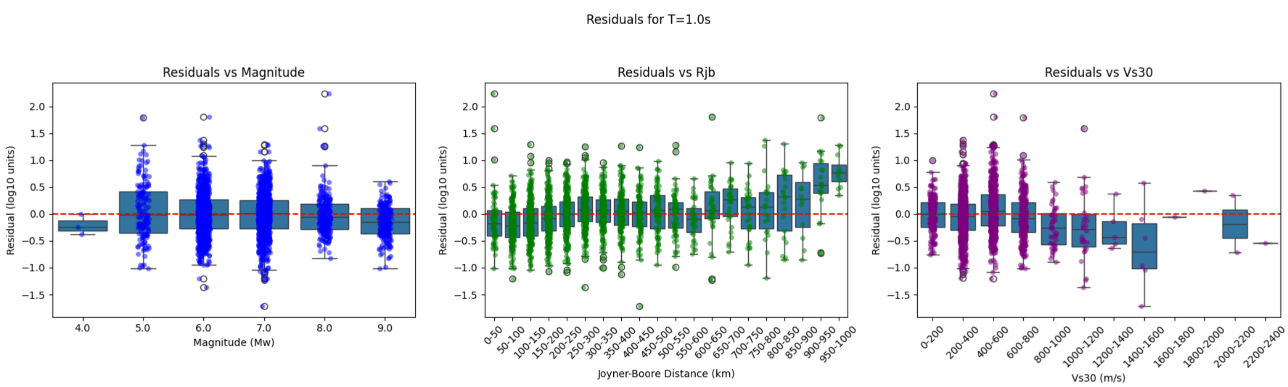
5. Residual Analysis

Parameter	Bias (Centering)	Spread (Variance)	Interpretation
Magnitude (Mw)	Centered around zero	Consistent across bins	No systematic under/over-prediction across magnitudes
Distance (Rjb)	Centered around zero	Increases at larger distances	Model performs well overall, but predictions become more variable far from source
Site Condition (Vs30)	Centered around zero	Higher variance at extreme Vs30	Site effects are well modeled; extremes have more uncertainty due to sparse data

The model is unbiased and robust across magnitude, distance, and site conditions, with only mild increases in variance at data-sparse extremes.



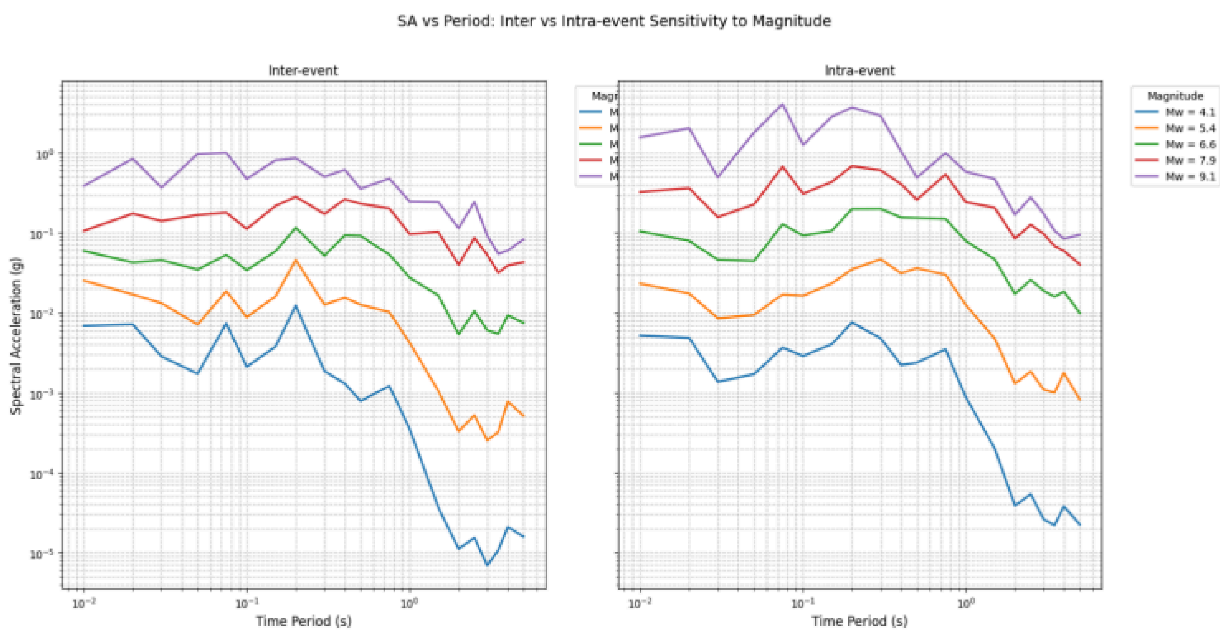




6. SA vs Period at Different Magnitudes

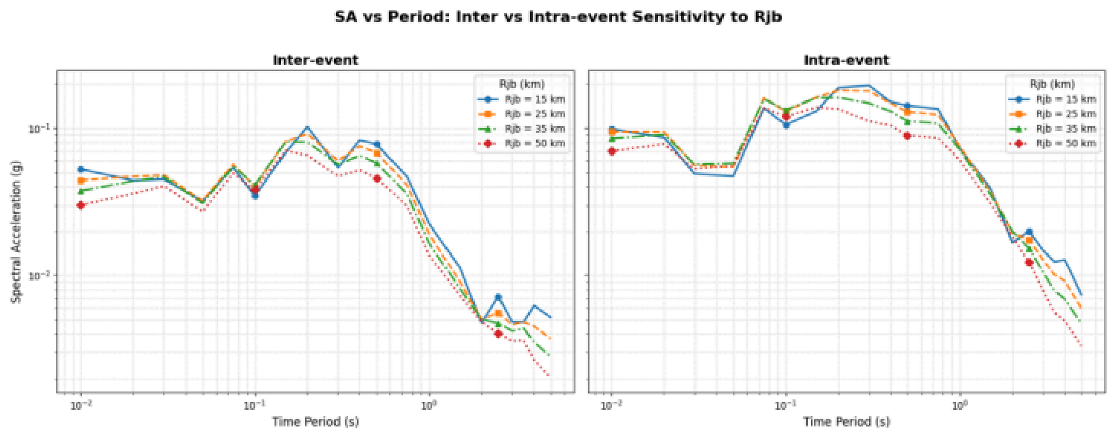
Aspect	Observation
Magnitude Effect	SA increases with earthquake magnitude across all periods.
Period Dependence	SA decreases as the time period increases.

Inter- vs Intra-event	Similar trends; intra-event SA slightly higher at some periods (esp. for high Mw).
Conclusion	SA is highly magnitude-sensitive; both variability components reflect this consistently.



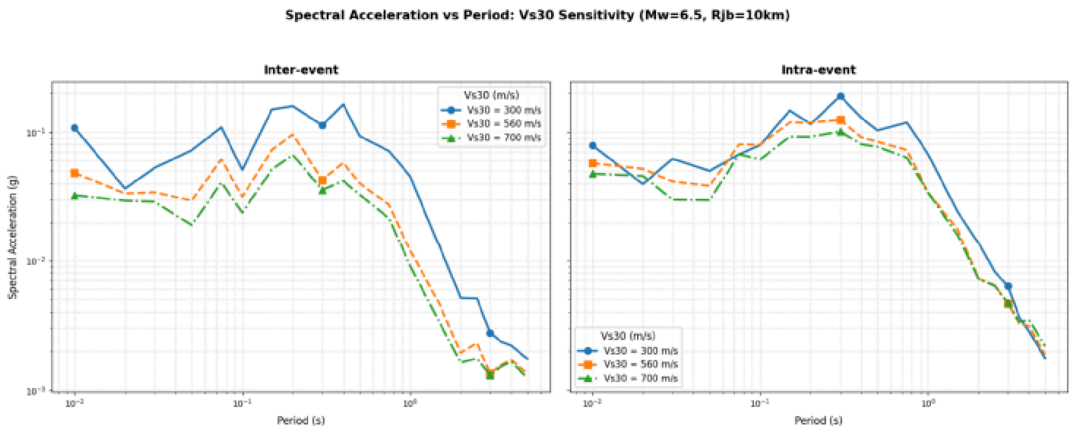
7. SA vs Period at Different Distances (Rjb)

Aspect	Observation
Distance Effect (Rjb)	SA decreases as distance from the source increases.
Period Dependence	SA decreases with increasing period for all distances.
Inter- vs Intra-event	Similar trends; intra-event SA slightly higher at intermediate periods.
Conclusion	Ground motion attenuation with distance is captured well in both components.



8. SA vs Period at Different Vs30

Aspect	Observation
Vs30	Lower Vs30 → higher SA across all periods.
Period Dependence	SA decreases with increasing period for all Vs30 levels.
Inter- vs Intra-event	Similar Vs30 sensitivity; intra-event slightly higher at short-to-mid periods.
Conclusion	Model effectively reflects site amplification; behavior consistent across components.



9. Ground Motion Physics with Respect to Distance (Rjb)

The analysis of spectral acceleration (SA) as a function of rupture distance (Rjb) provides several consistent and physically intuitive insights across both intra-event (ϕ) and inter-event (τ) components. Most notably, SA decreases systematically with increasing distance from the rupture, which is expected due to the attenuation of seismic energy as it propagates through the Earth.

This trend holds across all periods analyzed—0.01s, 0.1s, 1.0s, and 5.0s. The rate of this attenuation is especially pronounced at shorter periods (e.g., 0.01s and 0.1s), where ground motions are more sensitive to high-frequency energy that dissipates quickly over distance. In contrast, longer-period motions tend to attenuate more slowly, but still show a clear downward trend with Rjb.

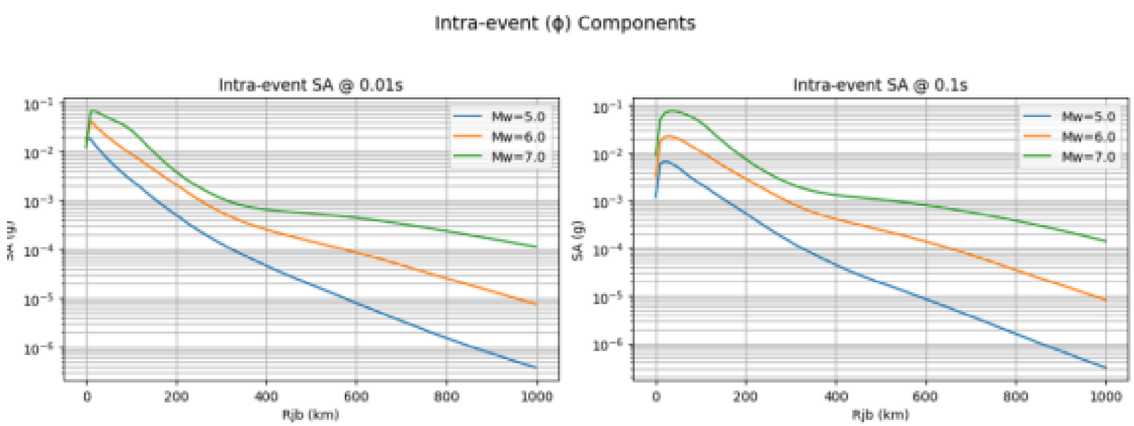
Magnitude also plays a strong role in shaping SA values. At any fixed distance, larger magnitude events (e.g., Mw 7.0) produce significantly higher ground motions than smaller events (e.g., Mw 5.0 or 6.0). The separation between different magnitude curves is preserved in both the intra- and inter-event results, illustrating a robust and consistent sensitivity of SA to earthquake size.

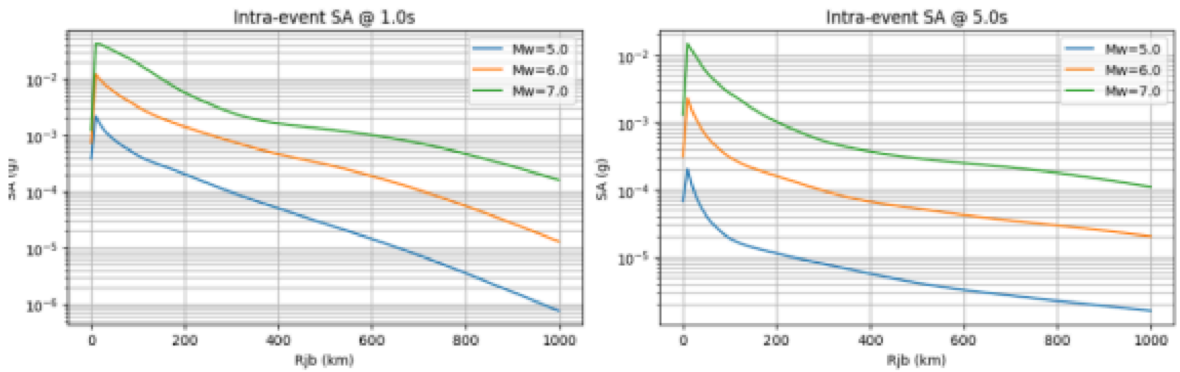
When comparing the intra- and inter-event components, their behavior is remarkably similar. The trends in SA with respect to both magnitude and distance are nearly identical, and the absolute SA values produced by the two components are closely aligned for corresponding input values. This suggests that both sources of variability—between events and within events—respond similarly to the physical parameters of the earthquake.

Conclusion

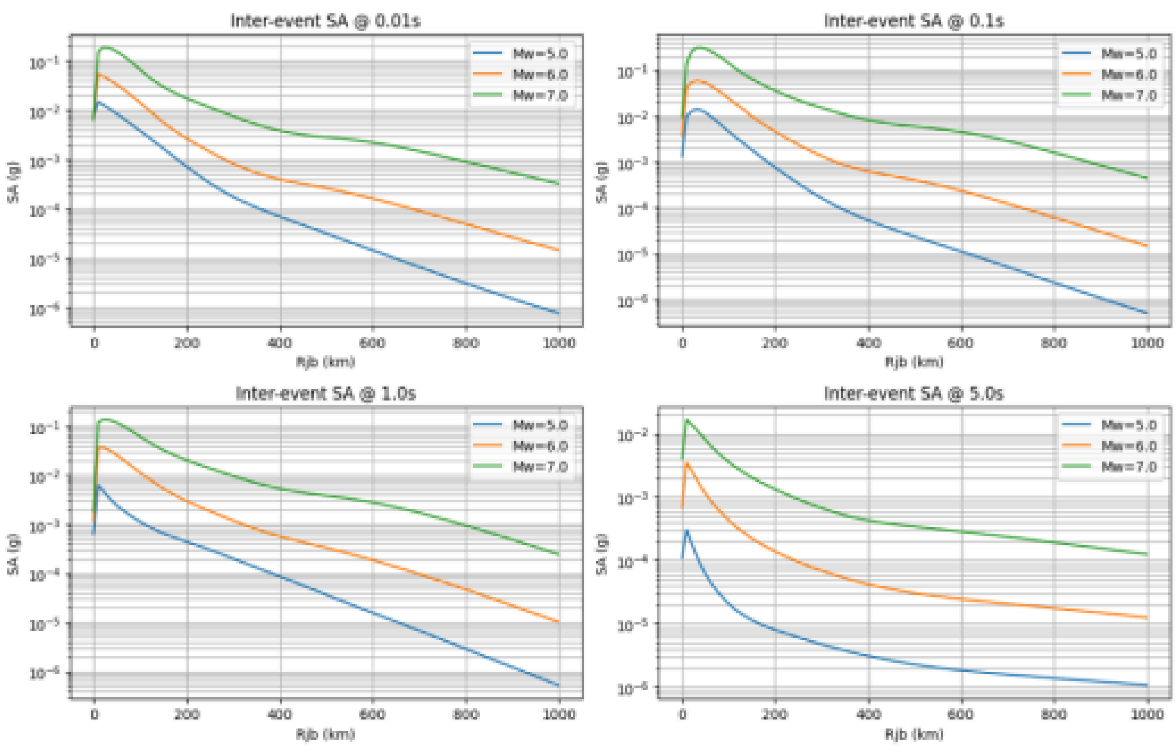
In summary, ground motion behavior with respect to Rjb aligns well with expected physical patterns: spectral acceleration diminishes with distance and increases with earthquake magnitude. These patterns are consistent across all periods and are captured equally well in both the intra-event and inter-event components of the model. The model thus reflects a realistic understanding of how seismic energy decays with distance and amplifies with earthquake size.

Aspect	Observation
Magnitude Sensitivity	Higher Mw leads to higher SA at any given distance for both inter- and intra-event.
Distance Sensitivity	SA decreases rapidly with increasing Rjb for all periods.
Period Dependence	SA drops more steeply with distance at shorter periods (e.g., 0.01s, 0.1s).
ϕ vs τ Comparison	Nearly identical trends and magnitudes; both respond similarly to Rjb and Mw.
Conclusion	Ground motions attenuate with Rjb and amplify with Mw consistently across both variability components and all periods.





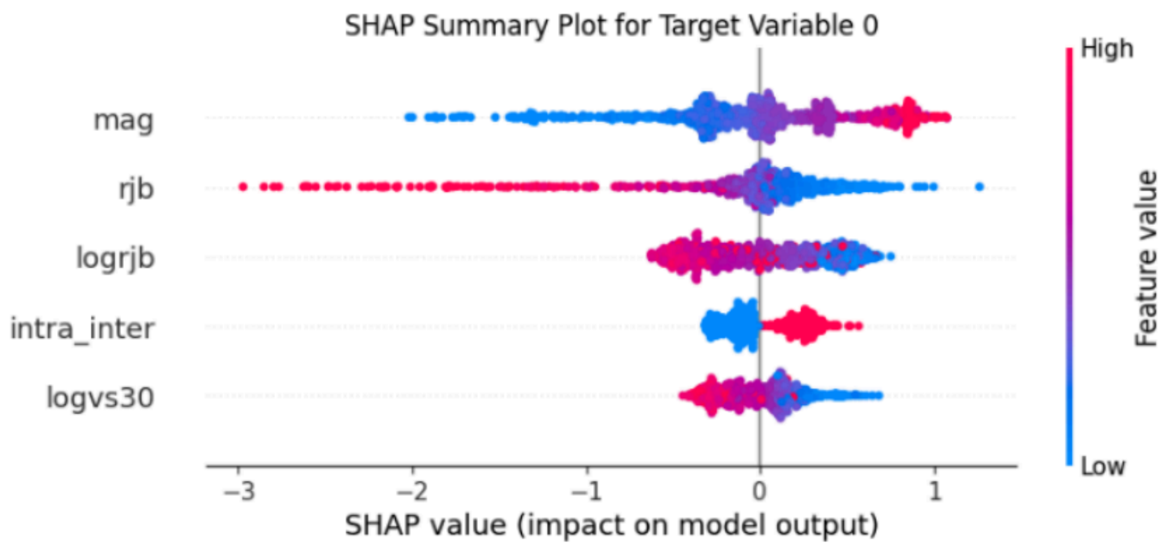
Inter-event (τ) Components



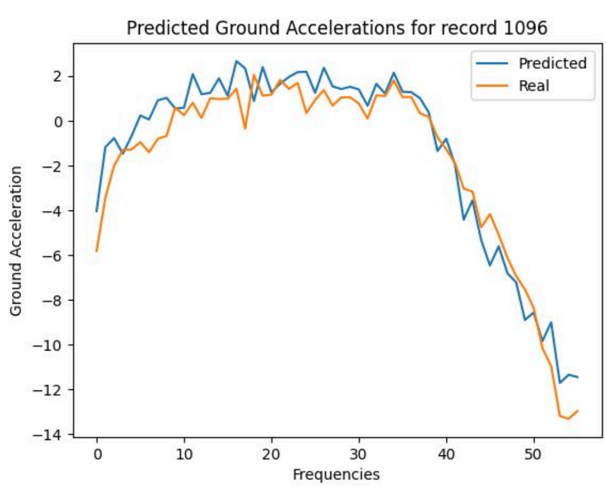
10. SHAP Analysis

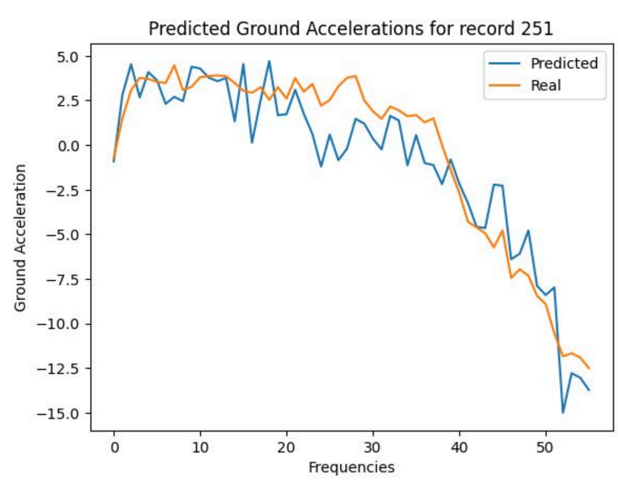
Feature	Impact on Output
Magnitude (mag)	High values (red) increase output; low values (blue) decrease it.
Distance (rjb)	High rjb/log(rjb) reduces output; low rjb increases it.

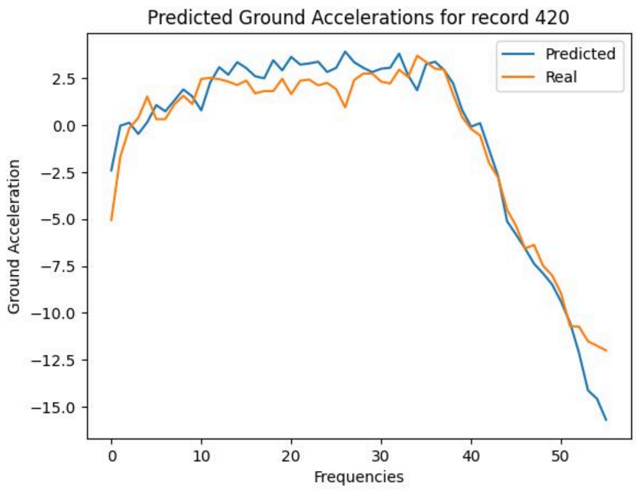
Intra_inter	Moderate positive effect; high values slightly increase output.
logvs30	Low values (soft soil) increase output; high values (stiff sites) decrease it.
Conclusion	Magnitude and distance dominate model behavior, consistent with ground motion physics.

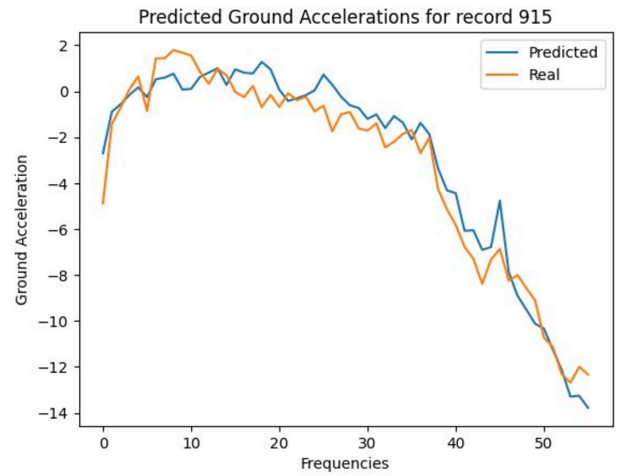


11. Predicted vs Actual Plots









12. Feature Importance

Feature	Importance (%)	Interpretation
Magnitude (mag)	44.3%	Primary predictor; SA increases significantly with earthquake size.
logrjb	25.1%	Key distance-related metric affecting attenuation.
rjb	20.9%	Combined with logrjb, emphasizes distance relevance.
Intra_inter	5.5%	Minor role; some contribution to output variability.
logvs30	4.2%	Least important; site condition has limited influence in model.

Magnitude and distance dominate model influence; intra/inter-event and site effects are secondary.