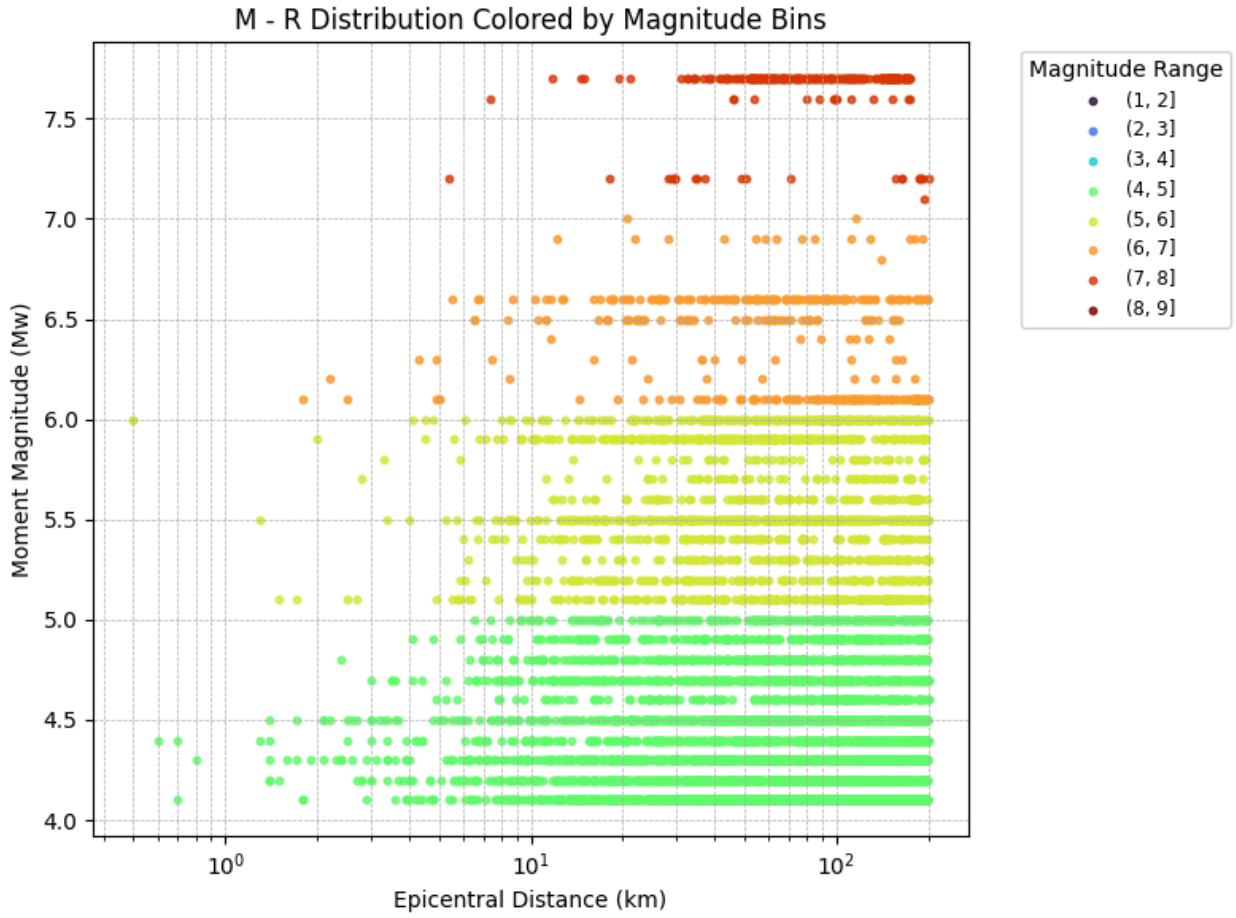
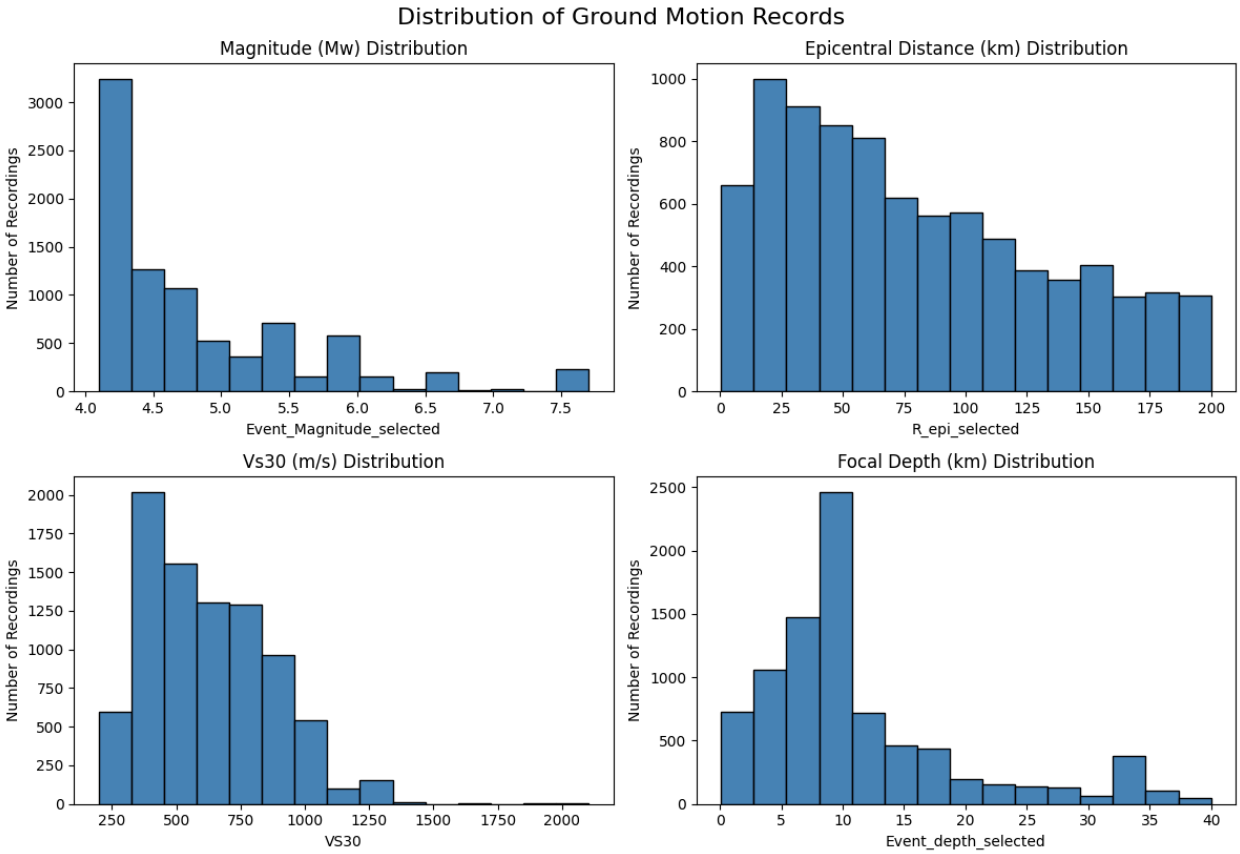
1. Magnitude vs Joyner-Boore Distance



- 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	Event_depth_selected
min	4.1000	0.5000	198.0000	0.1000
max	7.7000	199.9000	2104.2000	40.0000
mean	4.8315	79.5987	623.9816	11.1482
std	0.8117	53.8051	242.8279	8.2397
skewness	1.5924	0.5351	0.6112	1.5129
kurtosis	2.4603	-0.8112	0.0107	1.7629

Table 01 - Output Parameters:

	U_target_selected_1	U_target_selected_2	U_target_selected_3	U_target_selected_4	U_target_selected_5	U_target_selected_6	U_target_selected_7	U_target_selected_8	U_target_selected_9
min	0.0000	0.0000	0.0000	0.0000	0.0001	0.0002	0.0003	0.0004	0.0006
max	4836.5170	4302.4922	3097.6693	4299.3010	4713.7618	4196.1082	4130.3150	6415.0268	6400.9357
mean	10.0283	25.3087	30.2395	32.3795	36.3600	37.8630	40.1494	42.6016	45.3880
std	93.1098	162.5251	154.4057	162.0937	175.5214	171.9430	172.5549	188.0650	200.8263
skewness	24.2859	12.0879	9.2424	11.3707	10.8141	10.1882	8.3731	11.1739	12.4133
kurtosis	974.0350	185.9719	108.9522	196.7534	180.0279	151.6814	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.

ANN - Mixed Effects

Model Performance (R^2):

The R^2 values for all target variables are consistently high, ranging from 0.8239 to 0.8967.. This indicates that the models account for a substantial portion of the variance in each target, reflecting strong predictive performance across all periods.

Table 01 - Input Parameters:

	mag	rjb	logrjb	logvs30	intra_inter
min	4.1000	0.0100	-2.0000	1.7243	0.0000
max	9.1200	999.0898	2.9996	3.3483	1.0000
mean	6.8318	289.7475	2.3520	2.5906	0.4232
std	1.0028	196.9747	0.3695	0.2032	0.4941
skewness	0.7859	1.2926	-3.3307	-0.0870	0.3107
kurtosis	0.3906	1.5350	33.8885	0.1169	-1.9035

Table 01 - Output Parameters:

	T0pt010S	T0pt020S	T0pt030S	T0pt050S	T0pt075S	T0pt100S	\
min	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	
max	2.5801	2.7391	3.5567	4.9801	5.9791	3.6631	
mean	0.0304	0.0311	0.0330	0.0396	0.0499	0.0608	
std	0.0850	0.0884	0.0990	0.1280	0.1542	0.1829	
skewness	8.2602	8.5575	10.0383	11.3257	10.0677	7.6269	
kurtosis	120.2980	128.9357	190.2750	242.2775	208.1898	82.9457	

	T0pt150S	T0pt200S	T0pt300S	T0pt400S	T0pt500S	T0pt750S	\
min	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	
max	5.8752	6.2565	5.2520	4.2340	3.0608	2.2700	
mean	0.0715	0.0738	0.0678	0.0591	0.0515	0.0382	
std	0.2191	0.2259	0.2036	0.1681	0.1412	0.0969	
skewness	8.5839	8.8185	8.9577	7.8704	6.9268	6.5910	
kurtosis	117.0851	124.5151	131.3643	99.5985	68.6172	68.6205	

	T1pt000S	T1pt500S	T2pt000S	T2pt500S	T3pt000S	T3pt500S	\
min	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	
max	1.2481	1.3501	1.2663	0.6708	0.3824	0.3857	
mean	0.0300	0.0198	0.0143	0.0108	0.0084	0.0068	
std	0.0740	0.0509	0.0373	0.0272	0.0213	0.0176	
skewness	6.0280	7.8387	8.7858	6.9784	6.2945	6.8688	
kurtosis	51.9060	106.6552	156.0315	87.9723	60.6166	79.6645	

	T4pt000S	T5pt000S
min	0.0000	0.0000
max	0.2931	0.2265

mean	0.0055	0.0039
std	0.0140	0.0098
skewness	6.2210	5.9755
kurtosis	60.9231	57.1025

Input Parameters:

The input variables (mag, rjb, log(rjb), logvs30, intra_inter) exhibit a wide range, particularly for rjb and log(rjb), which show significant diversity.

High skewness and kurtosis in log(rjb) (skewness: -3.33, kurtosis: 33.89) indicate a heavy-tailed, left-skewed distribution.

Other parameters (mag, rjb) show moderate skewness, suggesting some asymmetry and outliers.

Output Parameters:

All output parameters (T0pt010S to T3pt500S) start at 0, with wide ranges and extremely high skewness and kurtosis.

For example, T0pt010S has skewness of 8.26 and kurtosis of 120.30, reflecting heavy-tailed, highly skewed distributions.

Means are significantly lower than maximum values, confirming the presence of long tails in the distributions.

Uncertainty Measures:

	Target Variable	R2	Inter-Std (τ)	Intra-Std (φ)	Total Std
0	T0pt010S	0.8666	0.6708	0.6867	0.9600
1	T0pt020S	0.8658	0.6747	0.6897	0.9648
2	T0pt030S	0.8636	0.6878	0.6966	0.9790
3	T0pt050S	0.8541	0.7215	0.7298	1.0262
4	T0pt075S	0.8394	0.7575	0.7851	1.0910
5	T0pt100S	0.8315	0.7750	0.8195	1.1280
6	T0pt150S	0.8365	0.7490	0.8168	1.1083
7	T0pt200S	0.8434	0.7258	0.7941	1.0758
8	T0pt300S	0.8591	0.6866	0.7351	1.0058
9	T0pt400S	0.8675	0.6673	0.6985	0.9660
10	T0pt500S	0.8700	0.6459	0.6825	0.9397
11	T0pt750S	0.8645	0.6164	0.6784	0.9166

12	T1pt000S	0.8587	0.5980	0.6883	0.9118
13	T1pt500S	0.8487	0.5586	0.7086	0.9023
14	T2pt000S	0.8475	0.5479	0.7103	0.8970
15	T2pt500S	0.8524	0.5298	0.7022	0.8797
16	T3pt000S	0.8583	0.5239	0.6907	0.8669
17	T3pt500S	0.8625	0.5219	0.6809	0.8579
18	T4pt000S	0.8678	0.5133	0.6655	0.8404
19	T5pt000S	0.8795	0.4989	0.6342	0.8069

● **Inter-Event Standard Deviation (τ):**

τ values range from approximately **0.4989 to 0.7750**, representing variability between different events. Lower values at longer periods (e.g., **T5pt000S**) indicate reduced inter-event variability for those targets. The highest inter-event variability is observed at **shorter periods (T0pt100S)**.

● **Intra-Event Standard Deviation (ϕ):**

ϕ values range between approximately **0.6342 and 0.8195**, capturing variability within individual events. Similar to τ, intra-event variability tends to decrease at longer periods, with the highest values observed at **shorter periods (T0pt100S)** and the lowest at **T5pt000S**.

● **Total Standard Deviation:**

This metric combines both inter- and intra-event variability. It is highest for **shorter periods (e.g., T0pt100S, T0pt150S)** and progressively decreases at longer periods (e.g., **T5pt000S**). The highest total standard deviation is **1.1280 (T0pt100S)**, while the lowest is **0.8069 (T5pt000S)**

Inter-Event Standard Deviation (τ) and Intra-Event Standard Deviation (ϕ) Decline with Increasing Periods:

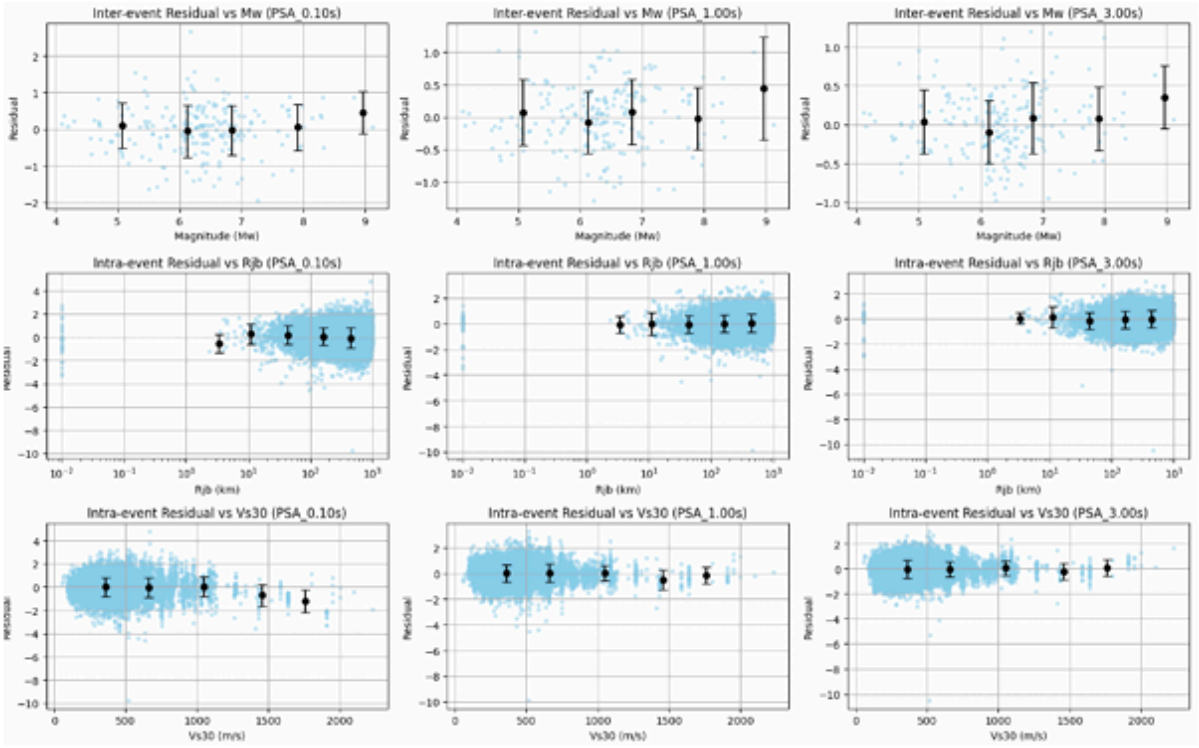
- Both τ and ϕ values generally decrease as the target period increases from **T0pt010S to T5pt000S**.
- This indicates that at **longer periods**, there is **greater stability** and **reduced variability**, both between events (inter-event) and within events (intra-event).

Higher Total Standard Deviation at Shorter Periods:

- The **Total Standard Deviation** is highest at shorter periods (e.g., **T0pt100S: 1.1280**), reflecting **greater uncertainty** in the predictions at these shorter periods.

- As the period increases, the **Total Standard Deviation** decreases, reaching the lowest value at **T5pt000S: 0.8069**, indicating that the model becomes more stable and reliable at longer periods.

Residual Plots



Inter-Event Residuals vs Magnitude (Mw):

- Residuals are centered around zero across all magnitude bins, with no significant bias.

- Consistent spread across magnitudes indicates balanced model performance for all earthquake sizes.

Intra-Event Residuals vs Rjb (Distance):

- Residuals slightly under-predict at smaller distances, approaching zero at larger distances.

- Higher variability near the source suggests greater prediction uncertainty for close distances.

Intra-Event Residuals vs Vs30 (Site Condition):

- Residuals are evenly centered around zero across all Vs30 values, with no clear trend.
- Consistent variability indicates the model captures site effects well.

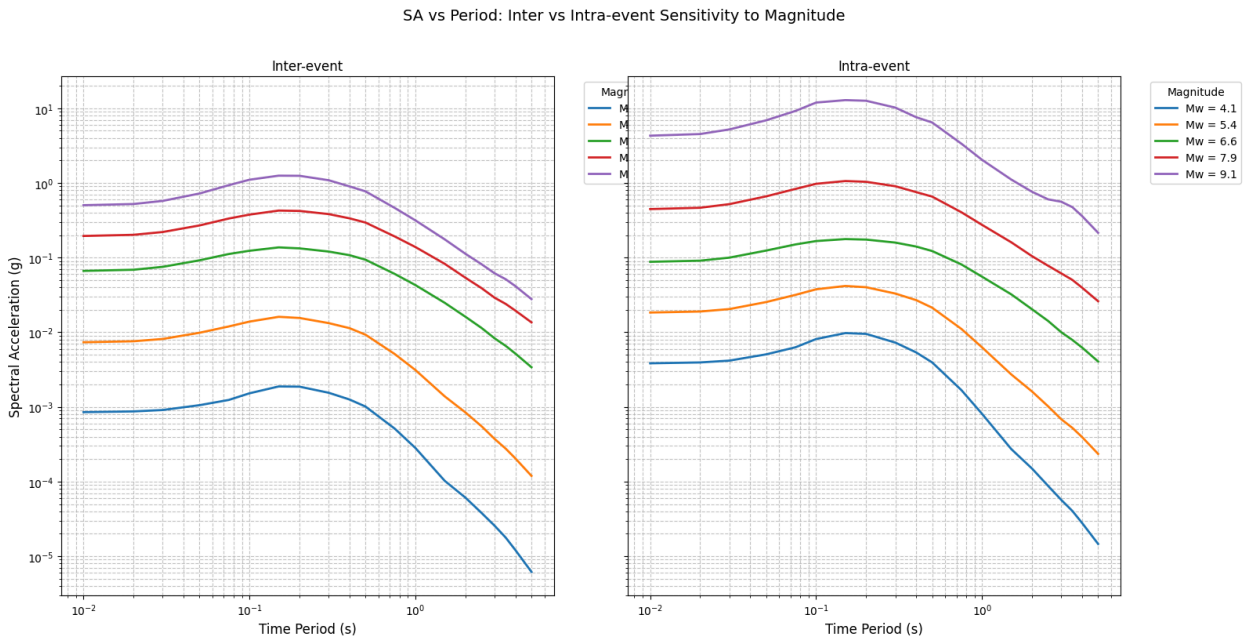
Overall Conclusion:

- The model shows no significant bias with respect to magnitude or site condition.

- Slight underestimation at close distances is noted, but residuals are generally well-behaved and centered around zero.

Ground Motion Physics

a. Spectral Acceleration vs Time Period at different magnitudes



1. Inter-Event Variability (Left Plot):

- Spectral Acceleration (SA) shows clear magnitude-dependent trends:
  - Higher magnitudes (Mw = 9.1) consistently produce higher SA values across all periods.
  - SA peaks around 0.2s to 1.0s, then decreases at longer periods.

- The relative separation between magnitude curves is consistent:
  - This suggests a strong and predictable relationship between magnitude and SA.

- Magnitude scaling is stable, with each magnitude shift maintaining a consistent gap.

2. Intra-Event Variability (Right Plot):

- SA is also magnitude-dependent, but the patterns differ slightly:
  - Higher magnitudes still produce higher SA values, but the scaling is less pronounced.
  - The curves generally decrease with increasing period for higher magnitudes.

- For lower magnitudes (Mw = 4.1), SA peaks at shorter periods and rapidly declines.

- The curves for higher magnitudes are smoother, suggesting more consistent ground motion characteristics for large events.

3. Comparative Insights (Inter vs Intra-Event):

- **Inter-Event Residuals (Left):** Capture the variability between different earthquake events:
    - The magnitude impact is strong and consistent.
    - This reflects how the overall energy release of an event affects ground motion.

- **Intra-Event Residuals (Right):** Capture the variability within a single event (site-specific effects):
    - The magnitude impact is present but less distinct.
    - Higher magnitudes show more stable SA across periods, while lower magnitudes have more variability.

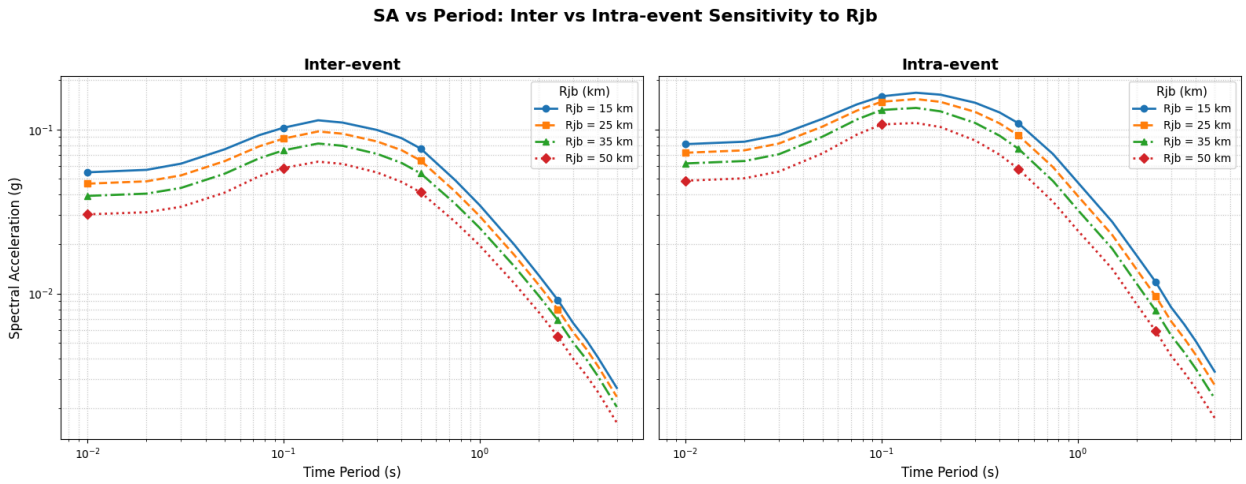
4. Seismic Design Implications:

- Inter-event residuals show that ground motion predictions must account for magnitude-dependent scaling.

- Intra-event residuals emphasize the need to account for site-specific effects, especially at lower magnitudes.

- The consistent trends across periods reinforce the importance of magnitude and site conditions in seismic hazard analysis.

b. Spectral Acceleration vs Time Period at different Joyner-Boore distance



Inter-Event Variability (Left Plot):

- Spectral Acceleration (SA) decreases with increasing distance (Rjb).
- The highest SA is observed at **Rjb = 15 km**, and the lowest at **Rjb = 50 km**.
- Peak SA occurs around 0.1s to 0.2s, with all curves showing a consistent decline at longer periods.
- The clear separation between distance curves indicates strong distance-dependent scaling.

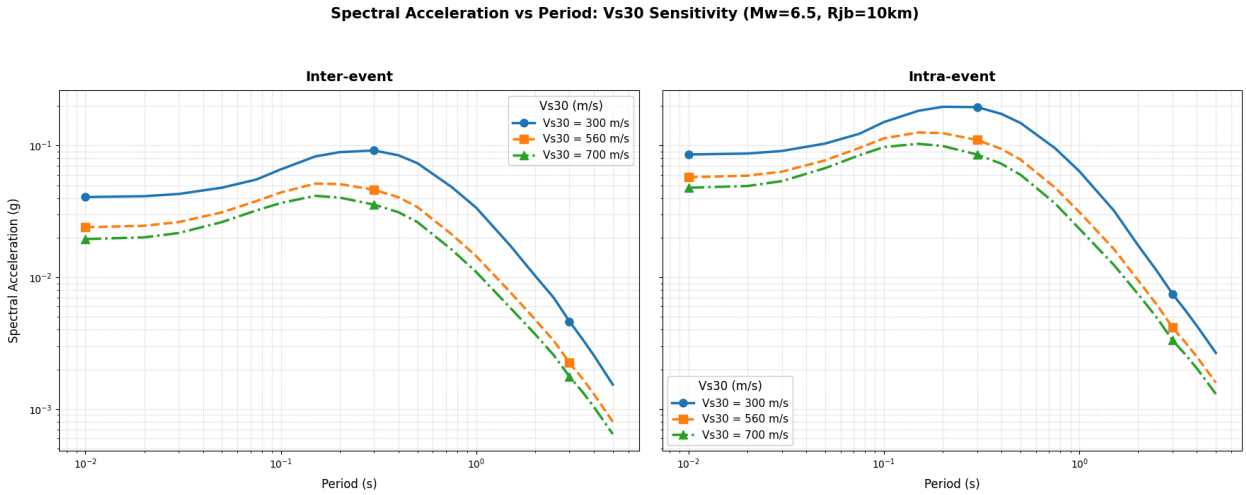
Intra-Event Variability (Right Plot):

- SA still decreases with distance (Rjb), but the curves are closer together.
- This indicates that, within a single event, distance has a smaller impact on SA.
- The peak period remains consistent (0.1s to 0.2s), with a smooth decline afterward.

Seismic Design Implications:

- SA is strongly distance-dependent between events (Inter-Event), but less so within a single event (Intra-Event).
- For seismic hazard analysis, distance must be carefully considered in ground motion models.

c. Spectral Acceleration vs Time Period at different Average Shear-Wave Velocities of the ground within the top 30 meters

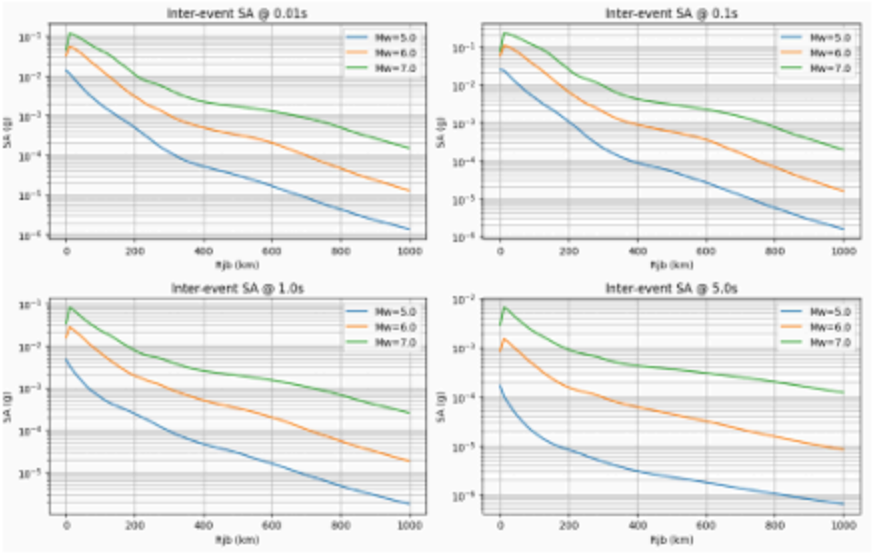


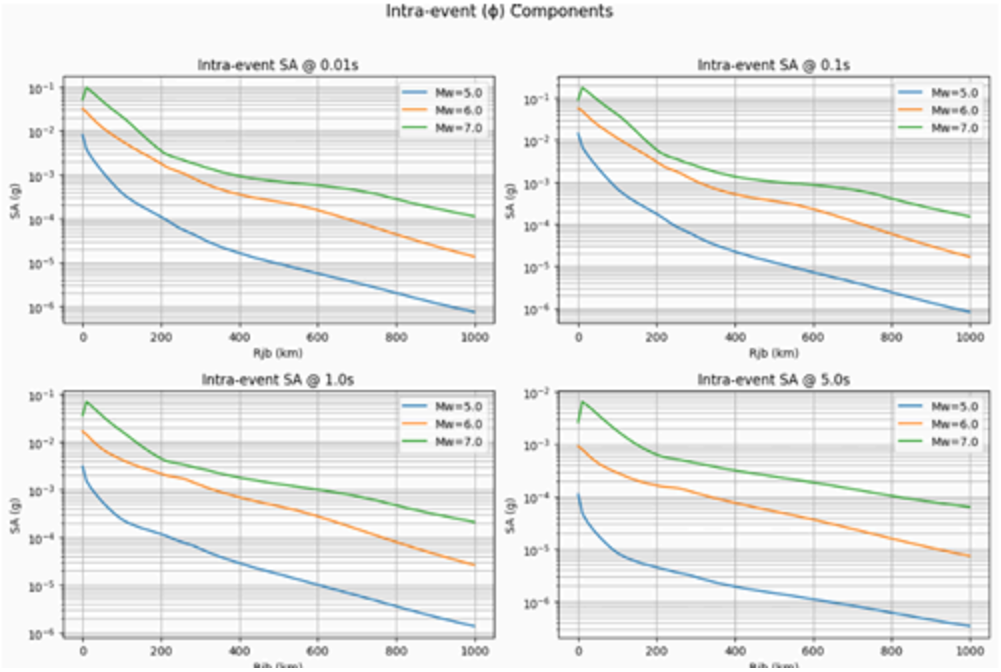
- **Inter-Event Variability (Left Plot):**
    - SA is highest for Vs30 = 300 m/s (soft soil) and lowest for Vs30 = 700 m/s (hard rock).
    - The clear separation between curves shows strong site condition sensitivity.
    - SA peaks around 0.1s to 0.2s, then decreases for longer periods.

- Intra-Event Variability (Right Plot):
    - SA follows a similar pattern but with slightly closer curves, indicating reduced Vs30 impact within a single event.
    - Soft soils (Vs30 = 300 m/s) consistently produce higher SA across all periods.

- Seismic Design Implications:
    - SA is highly sensitive to Vs30, with softer soils amplifying ground motion.
    - This highlights the importance of site conditions in seismic hazard assessments.

Ground Motion Physics wrt rjb





Inference from the Plots

● Magnitude Effect: For all periods and both inter-event and intra-event components, spectral acceleration (SA) increases with earthquake magnitude. Mw 7.0 events produce the highest SA, followed by Mw 6.0 and Mw 5.0.

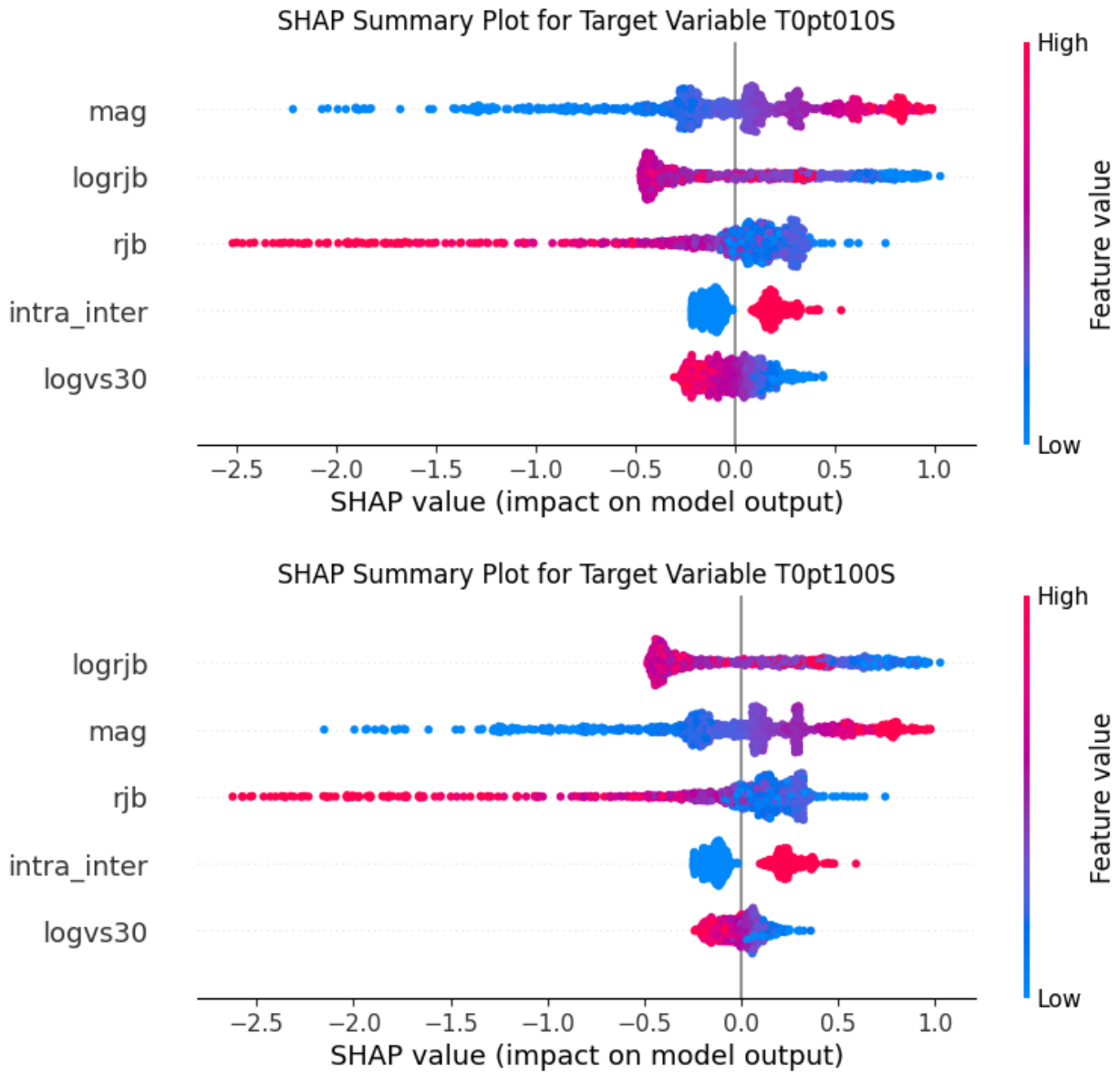
● Distance Effect: SA decreases rapidly with increasing rupture distance (Rjb). This decay is steepest at short distances and becomes more gradual at larger distances.

● Period Dependence: The overall pattern of SA decay with distance is similar across all periods (0.01s, 0.1s, 1.0s, 5.0s), but absolute SA values decrease for longer periods.

● Component Comparison: The trends for inter-event and intra-event components are nearly identical, indicating that both types of ground motion variability respond similarly to changes in magnitude and distance.

● Logarithmic Scale: The use of a log scale for SA and Rjb highlights the exponential decay and wide range of SA values.

SHAP Analysis



Magnitude (mag):

- Higher magnitudes (red) generally increase the model output (positive SHAP values).
- This aligns with the expected effect of larger magnitudes causing higher ground motions.

log(Rjb) and Rjb:

- Both variables have mixed effects on the model, but high values (red) reduce the output.
- This suggests that larger distances (Rjb) reduce ground motion intensity.

Intra_Inter:

- The impact is relatively consistent, with low values (blue) slightly reducing SA predictions.

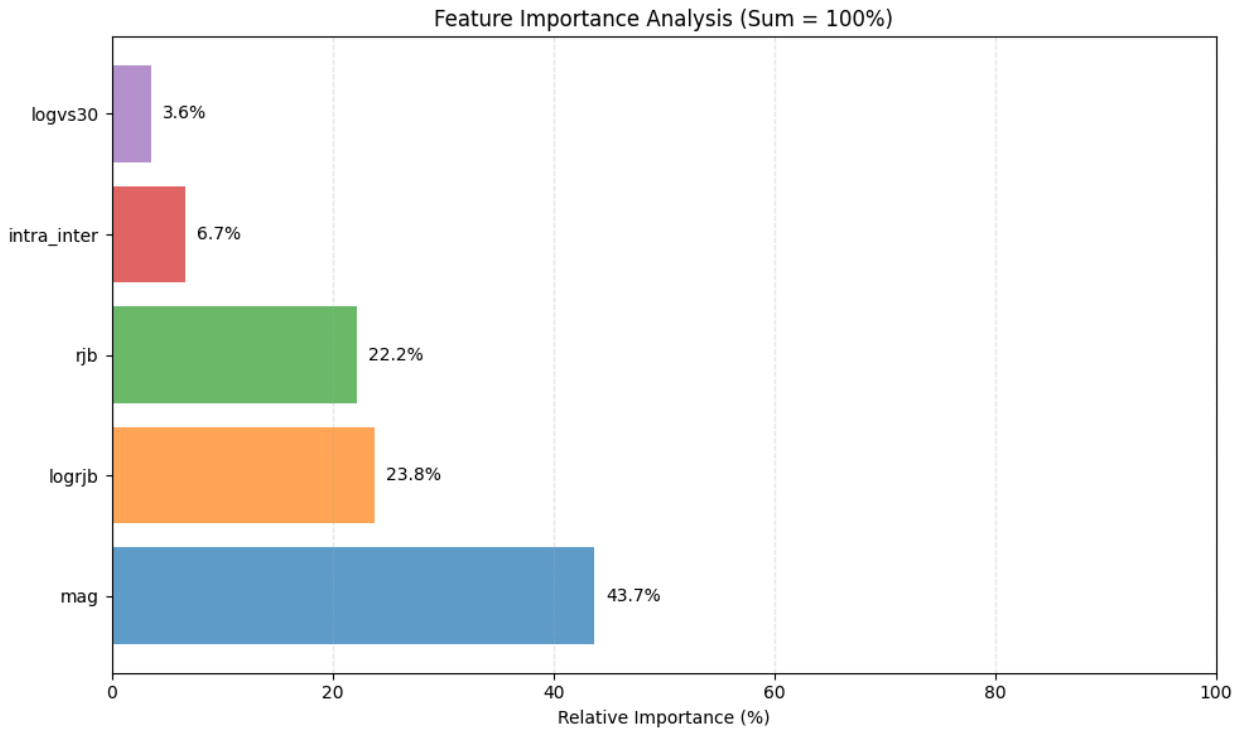
log(Vs30):

- Higher Vs30 values (red) strongly reduce the model output (negative SHAP values).
- This aligns with the concept that harder site conditions (higher Vs30) reduce ground motion.

Seismic Design Implications:

- The model is most sensitive to **Magnitude (mag)** and **log(Vs30)**.
- Distance (Rjb) has a complex, non-linear impact, while site condition (Vs30) consistently reduces ground motion.

Feature importance analysis plot



Magnitude (mag):

- Dominates with the highest importance (43.7%), highlighting its critical role in predicting ground motion.

log(Rjb) (23.8%) and Rjb (22.2%):

- Combined, these two distance parameters account for nearly half of the model's predictive power.
- This indicates the significant impact of distance on ground motion.

Intra_Inter (6.7%):

- Represents the intra- and inter-event variability, moderately influencing predictions.

log(Vs30) (3.6%):

- Has the lowest importance, suggesting that site condition (Vs30) has a smaller impact compared to magnitude and distance.

Seismic Design Implications:

- Magnitude and distance (Rjb) are the primary drivers of ground motion predictions.

- Site condition (Vs30) is relatively less critical in this model.