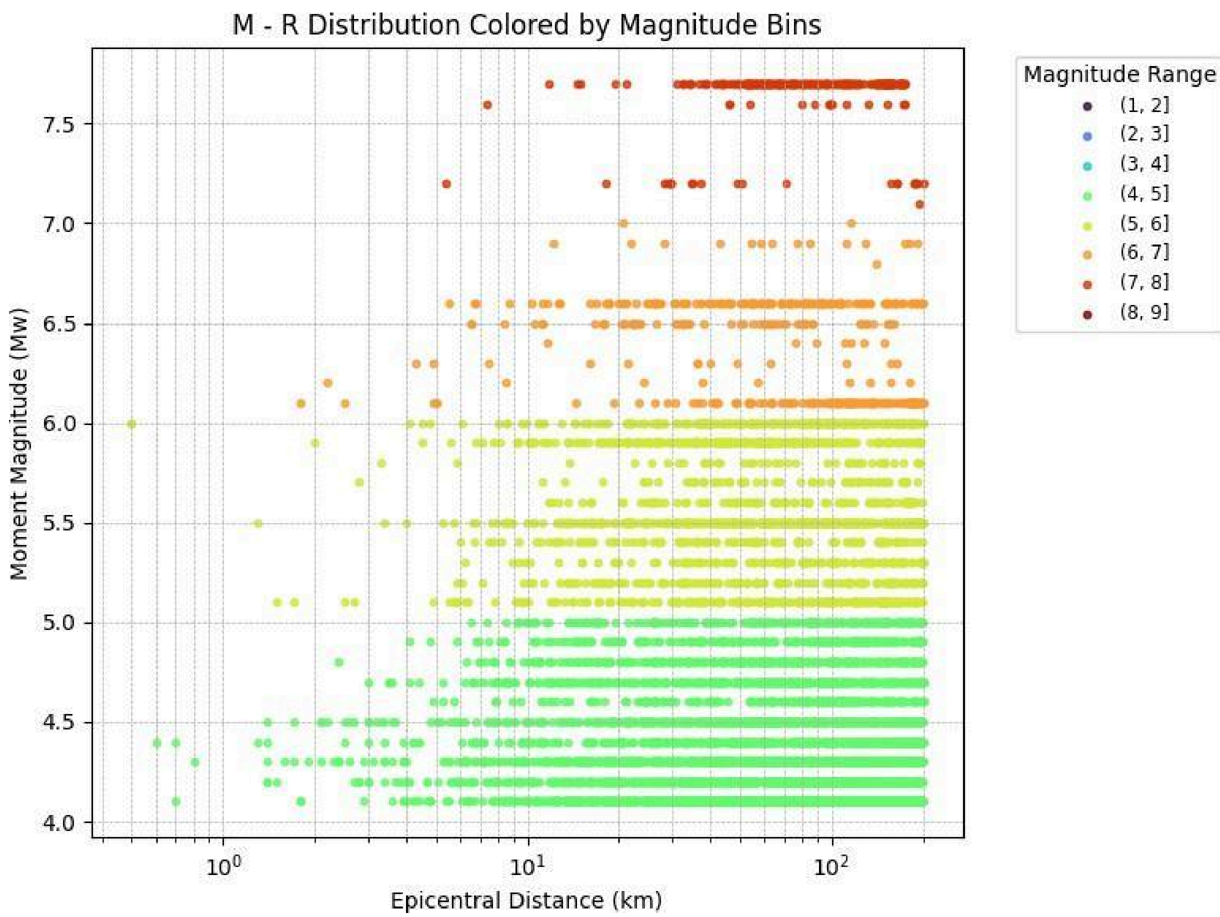
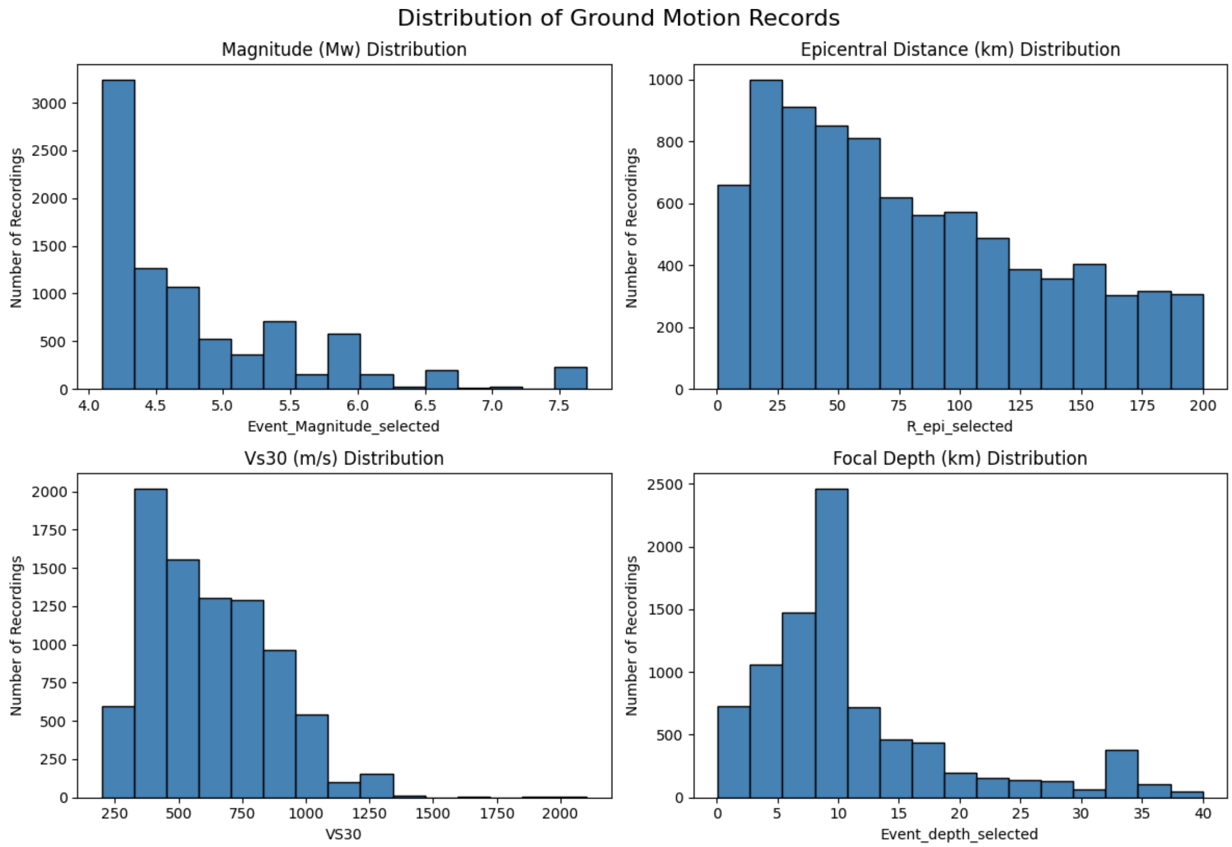
Long Short Term Memory (LSTMs)

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
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.

Table 2- target wise metrics

	Target Variable	R2	Inter-Std (τ)	Intra-Std (ϕ)	Total Std
0	T0pt010S	0.8820	0.6162	0.6739	0.9131
1	T0pt020S	0.8813	0.6196	0.6766	0.9175
2	T0pt030S	0.8795	0.6313	0.6834	0.9304
3	T0pt050S	0.8711	0.6628	0.7156	0.9754
4	T0pt075S	0.8581	0.6911	0.7693	1.0341
5	T0pt100S	0.8512	0.7037	0.8039	1.0683
6	T0pt150S	0.8549	0.6772	0.8027	1.0502
7	T0pt200S	0.8606	0.6598	0.7819	1.0231
8	T0pt300S	0.8741	0.6285	0.7247	0.9593
9	T0pt400S	0.8809	0.6216	0.6893	0.9282
10	T0pt500S	0.8827	0.6106	0.6730	0.9087
11	T0pt750S	0.8770	0.5920	0.6689	0.8933
12	T1pt000S	0.8715	0.5809	0.6777	0.8926
13	T1pt500S	0.8625	0.5433	0.6949	0.8821
14	T2pt000S	0.8616	0.5196	0.6959	0.8685
15	T2pt500S	0.8659	0.4981	0.6870	0.8486
16	T3pt000S	0.8709	0.4885	0.6774	0.8351
17	T3pt500S	0.8753	0.4883	0.6679	0.8274
18	T4pt000S	0.8805	0.4785	0.6526	0.8092
19	T5pt000S	0.8917	0.4642	0.6214	0.7756

Model Performance (R^2):
The R^2 values for all target variables are consistently high, ranging from 0.8512 to 0.8917. This indicates that the models account for a substantial portion of the variance in each target, reflecting strong predictive performance across all periods.

Uncertainty Measures:

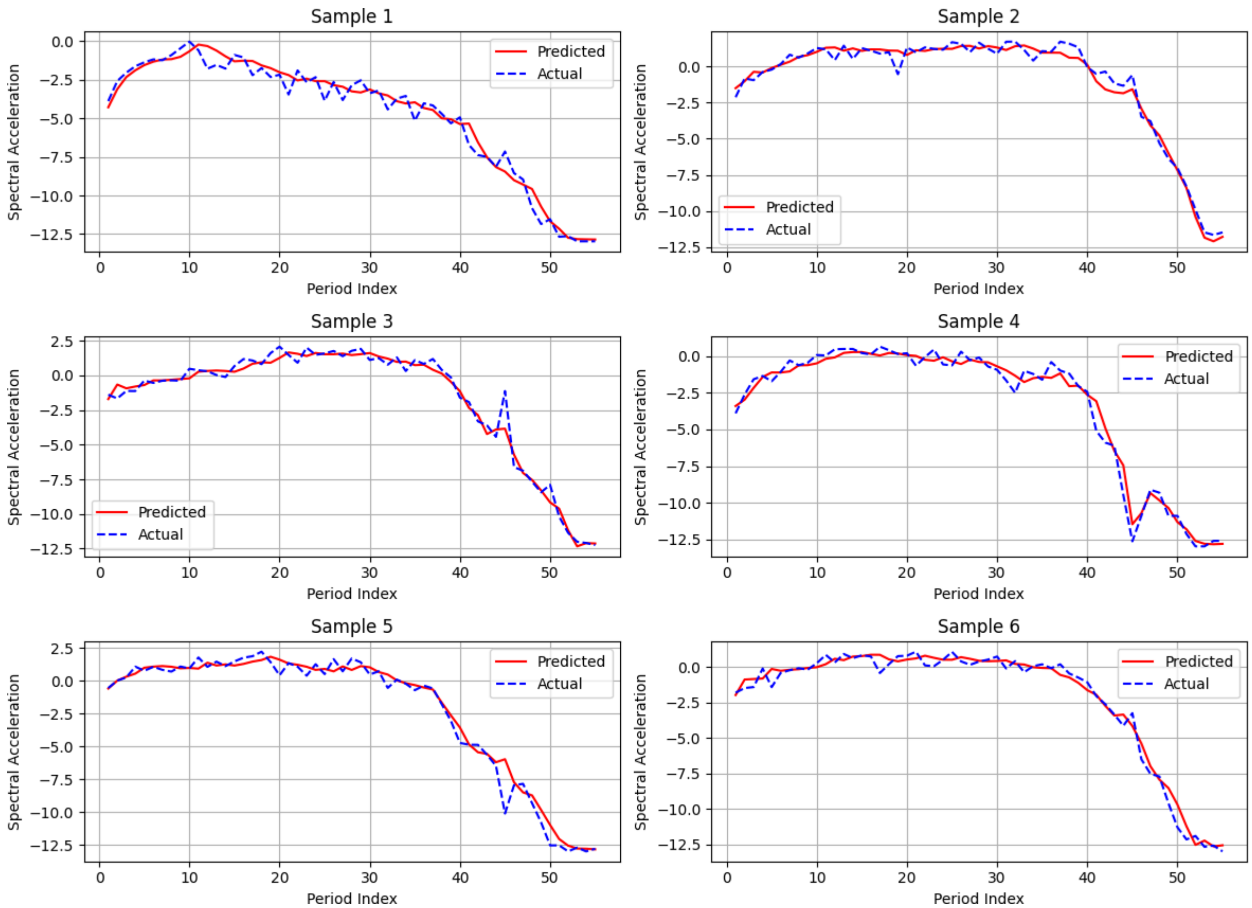
- **Inter-Event Standard Deviation (τ):**
τ values range from approximately 0.464 to 0.793, representing variability between different events. Lower values at longer periods (e.g., T5pt000S) suggest reduced inter-event variability for those

targets.

- **Intra-Event Standard Deviation (ϕ):**
  ϕ values fall between roughly 0.621 and 0.803, capturing variability within individual events. Similar to τ, intra-event variability tends to be lower at longer periods.

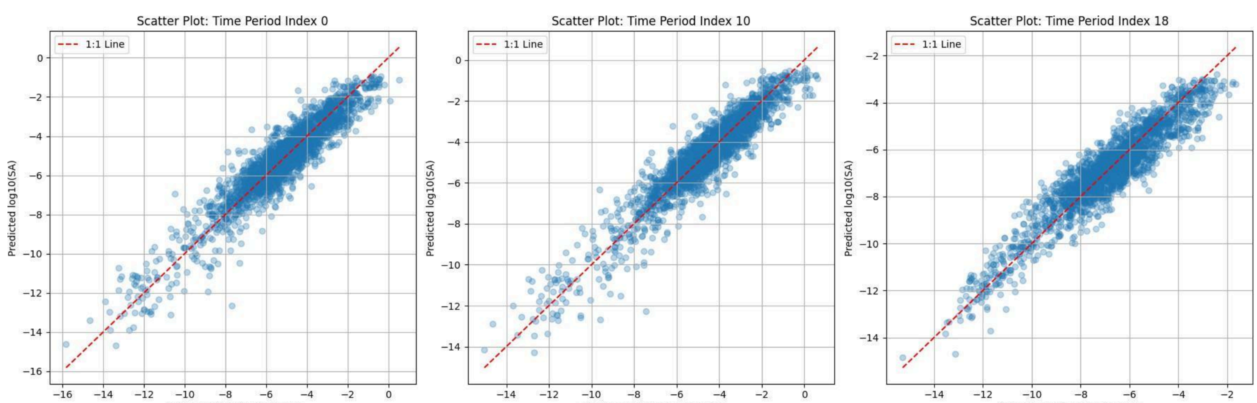
- **Total Standard Deviation:**
  This metric combines both inter- and intra-event variability. It is highest for shorter periods (e.g., T0pt100S, T0pt150S) and progressively decreases at longer periods (e.g., T5pt000S).

Trend Insights:
Both inter-event and intra-event standard deviations decline as the period increases, indicating greater stability and reduced variability in predictions at longer periods. Conversely, higher total standard deviations at shorter periods reflect increased uncertainty in those predictions.



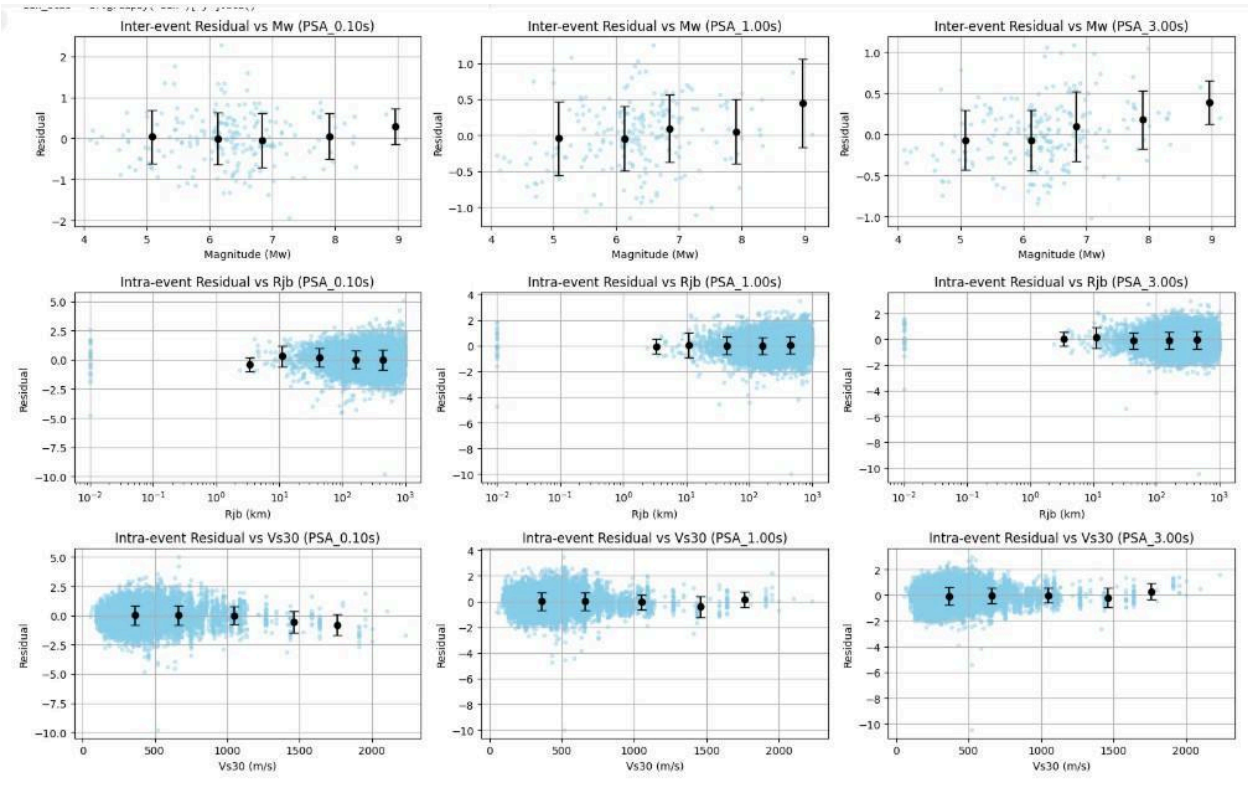
The above image shows the Actual vs Predicted image for the LSTM model.

4. Correlation plots:



We can see from the above image that the values are highly dense around the centerline.

5. Residual Plots



Inference from Residual Plots

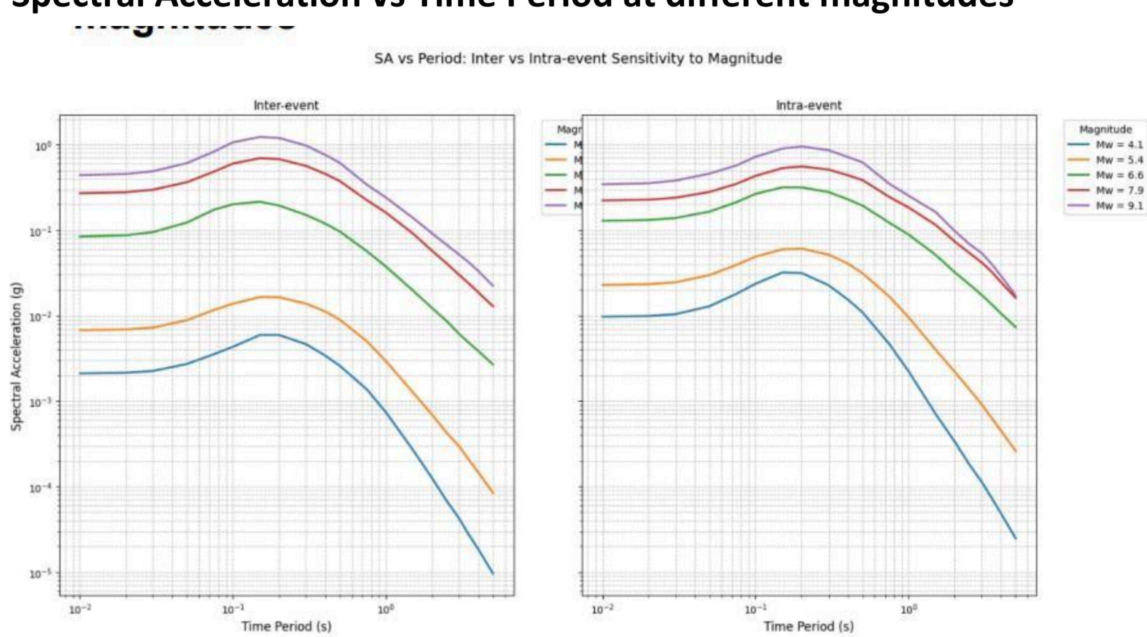
- **Inter-event Residuals vs Magnitude (Mw):**
  Residuals remain centered around zero across all magnitude bins, with no discernible trend as magnitude increases. The spread of residuals (represented by error bars) is uniform, suggesting that the model does not exhibit magnitude-dependent bias in PSA predictions at 0.1s, 1.0s, and 3.0s.
- **Intra-event Residuals vs Joyner-Boore Distance (Rjb):**
  Residuals are also centered near zero across distance bins, with no evident trend related to increasing distance. The consistent spread indicates that the model performs equally well at varying distances, without systematic over- or under-prediction.
- **Intra-event Residuals vs Vs30 (Shear-Wave Velocity):**
  Residuals remain close to zero across different Vs30 bins, showing no

significant site-condition-related bias. The variability is stable across all Vs30 values, reinforcing the model’s robustness.

- **Overall Conclusion:**
  Residuals show no meaningful trends or biases concerning magnitude, distance, or site conditions. The model predictions appear unbiased across all input parameters, with consistent variability, indicating reliable and well-calibrated performance.

6. Ground Motion Physics

a. Spectral Acceleration vs Time Period at different magnitudes



Insights from Inter- and Intra-event Plots:

- **Magnitude Influence:**
  Spectral acceleration (SA) increases with earthquake magnitude. High-magnitude events (e.g., Mw 9.1) consistently produce greater SA across all periods compared to lower-magnitude events (e.g., Mw 4.1).

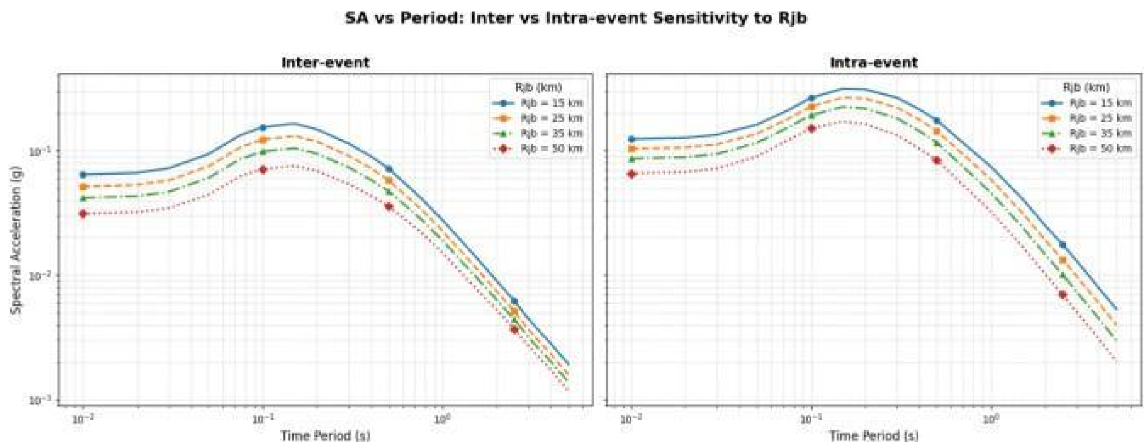
- **Period Dependence:**
  SA reaches its peak at intermediate periods (approximately 0.2–0.5 seconds) across all magnitudes and decreases at both shorter and longer periods.

- **Inter- vs Intra-event Consistency:**
  Both components show similar trends, with clear separation between magnitudes, confirming that SA is strongly magnitude-dependent in both cases.

- **Logarithmic Scaling:**
  The use of log-log plots underscores the wide range of SA and the exponential relationship between magnitude and ground motion intensity.

Summary:
Spectral acceleration is highly sensitive to earthquake magnitude and period. It increases with magnitude, peaks at intermediate periods, and declines at the extremes. Both inter- and intra-event components reflect this pattern, highlighting the strong physical relationship between magnitude and ground motion behavior.

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



- **Distance Effect:**
  SA decreases as Rjb increases. Close distances (e.g., 15 km) yield higher SA, while farther distances (e.g., 50 km) show reduced ground motion, for both inter- and intra-event components.

- **Period Sensitivity:**
  Across all distances, SA peaks at intermediate periods (0.2–0.5 seconds) and drops at shorter and longer periods.

- **Inter- vs Intra-event Similarity:**
  Both variability components show consistent separation by distance, indicating that SA's sensitivity to distance is mirrored across inter- and intra-event effects.

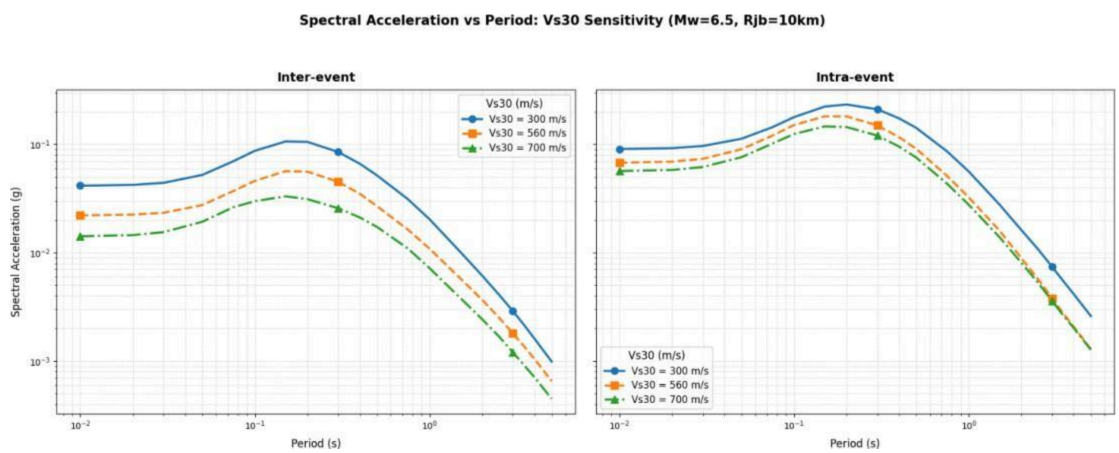
- **Use of Log Scales:**
  Log-log plots effectively display the steep attenuation of SA with increasing distance and highlight its wide dynamic range.

Summary:

Spectral acceleration diminishes with increasing distance from the source.

This decay pattern is consistently observed in both inter- and intra-event components. The highest ground motions occur at closer distances and intermediate periods, emphasizing the critical role of source proximity in seismic hazard modeling.

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



Key Insights:

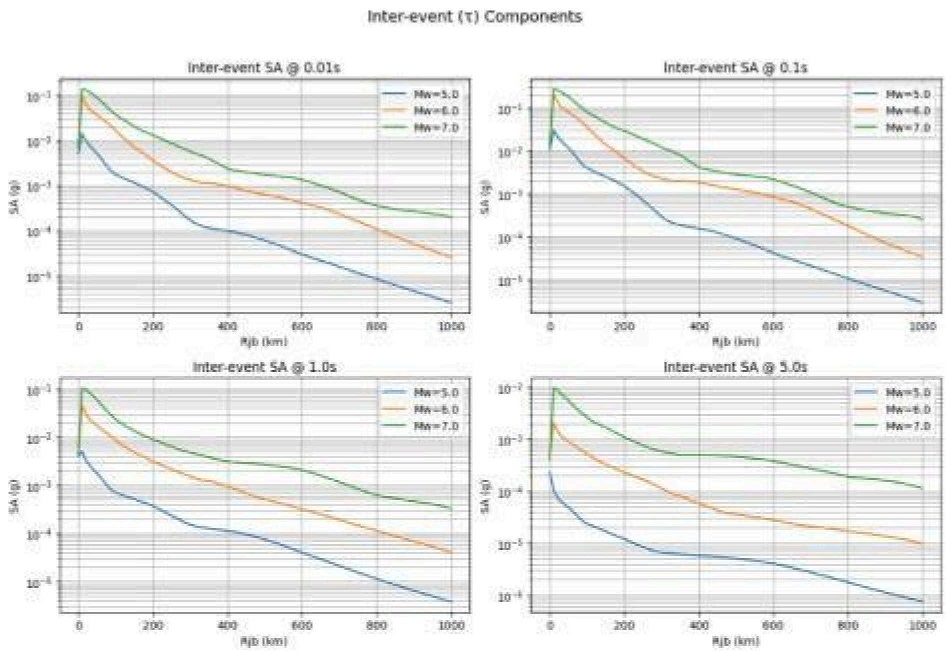
- **Vs30 Effect:**
  SA decreases with increasing Vs30. Sites with lower Vs30 (e.g., 300 m/s, soft soil) exhibit higher SA, while those with higher Vs30 (e.g., 700 m/s, rock) show lower ground motions. This relationship is evident in both inter- and intra-event components.

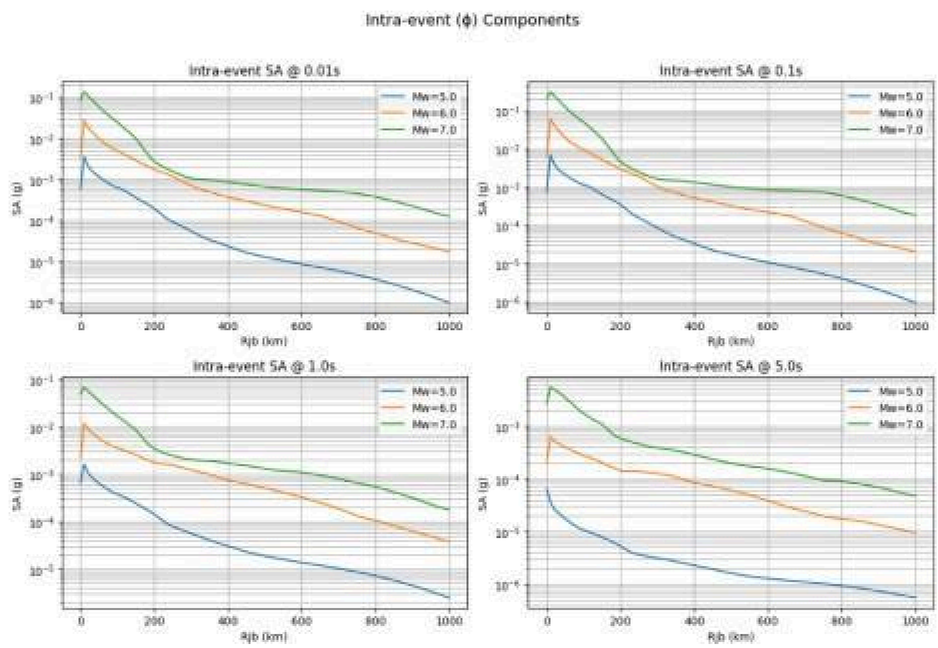
- **Period Dependence:**
  SA peaks at intermediate periods (0.2–0.5 seconds) regardless of Vs30 value and diminishes at the spectrum's ends.

- **Consistency Between Components:**
  The separation between curves across different Vs30 levels is consistent for both inter- and intra-event variability, indicating similar sensitivity to site effects.

Summary:
Softer soils (lower Vs30) are associated with higher spectral acceleration, while stiffer sites exhibit reduced SA. This trend is uniform across all periods and is captured similarly in both inter- and intra-event components, highlighting the significant influence of site conditions on seismic ground motions.

7. Ground Motion Physics wrt rjb





Insights from SA vs Rjb for Inter- and Intra-event Components:

- **Magnitude Dependency:**
  Across all periods (0.01s, 0.1s, 1.0s, 5.0s), SA increases with magnitude. Larger earthquakes (e.g., Mw 7.0) generate higher SA

compared to smaller events (e.g., Mw 5.0).

- **Distance Effect:**
  SA decreases rapidly with increasing Rjb, especially at short distances. The rate of decay slows at greater distances. This trend is evident for both inter- and intra-event components.

- **Period Behavior:**
  SA is highest at shorter periods (e.g., 0.01s, 0.1s) and gradually reduces at longer periods. However, the overall trend of SA decreasing with distance and increasing with magnitude remains consistent.

- **Component Comparison:**
  Both ϕ (intra-event) and τ (inter-event) components display nearly identical sensitivity to magnitude and distance, reinforcing their shared dependence on these key physical parameters.

Summary:
Spectral acceleration exhibits a clear inverse relationship with distance and a direct relationship with magnitude across all periods. Both inter- and intra-event components mirror these trends, affirming that the underlying ground motion physics are consistently reflected in both sources of variability.