MODELING OF INDIAN STRONG MOTION DATA USING EMPIRICAL MODE DECOMPOSITION TECHNIQUE

S SANGEETHA

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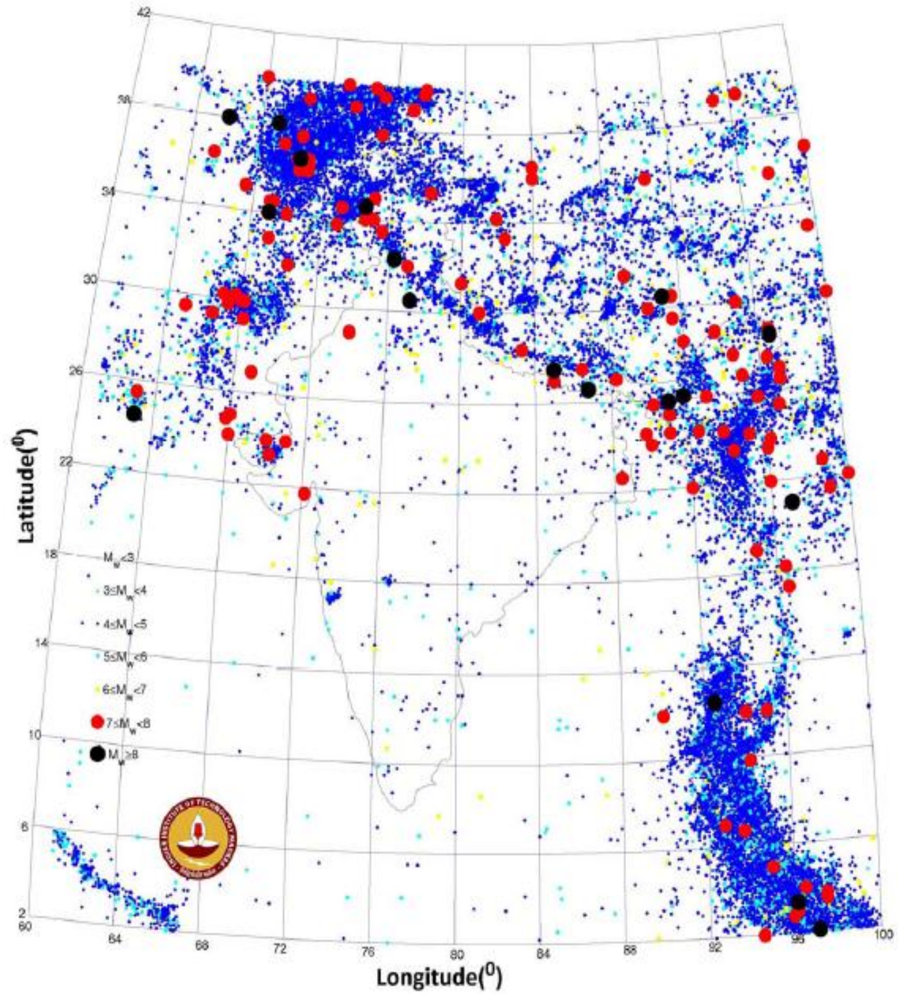
INTRODUCTION

- Himalayas and the north-east are seismically more active regions in India.
- Continent – continent boundary
- Faults are active in this region.
- Has produced many damaging great earthquakes ($M_w > 6$)
- Raised concerns about when and where the next earthquake will occur.
- Some researchers believe future events to occur at same place where past events happened

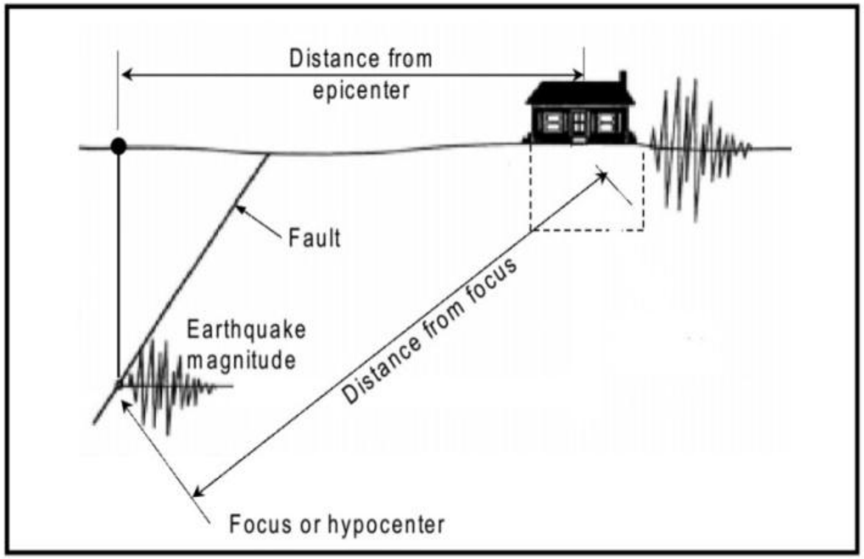


SEISMICITY MAP OF INDIA (NDMA REPORT)

(38860 events of Mw ≥4 including foreshocks and aftershocks)

INTRODUCTION

- ➢ Engineers are interested in the vibrations caused during an earthquake
- ➢ Ground motions are the key input in earthquake resistant design
- ➢ Seismic analysis of structures requires
- ✓ Peak Ground Acceleration (PGA)
- ✓ Spectral Acceleration (S_a)
- ✓ Non-linear analysis → acceleration time histories
- ➢ Structures has to be safe in future
- ➢ Brings the need for the estimation of future ground motions



How to estimate ground motions for future Earthquake?

ESTIMATION OF GROUND MOTIONS FOR FUTURE EARTHQUAKE

Step 1: Characterization of earthquake acceleration time histories

Step 2: Simulation of ground motion using the estimated strong motion parameters

CHARACTERIZATION OF EARTHQUAKE ACCELERATION

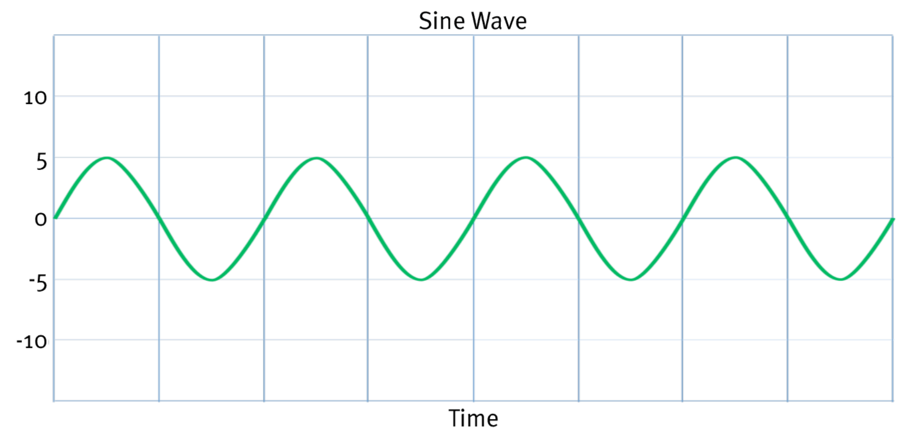
FOURIER ANALYSIS

The simplest model for a signal is given by circular functions of the type

$$x(t) = a\sin(2\pi\omega t) \text{ (or) } a\cos(2\pi\omega t)$$

✓ Stationary signals and Linear systems

✓Design of less important structures



EMPIRICAL MODE DECOMPOSITION

✓Physical process are mostly nonstationary and nonlinear in nature

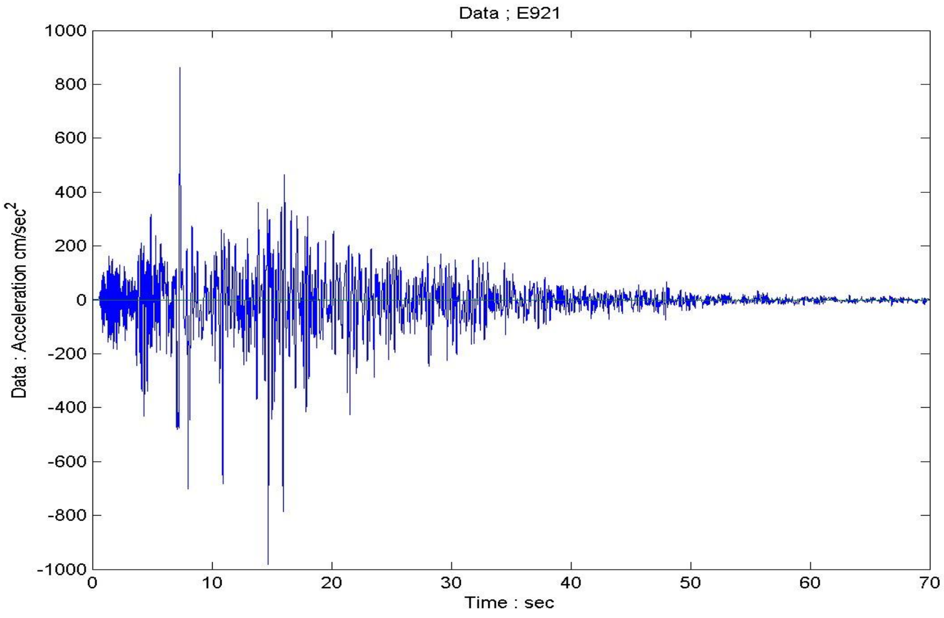
✓Can be represented in terms of amplitude and frequency modulated (AM–FM) components

$$x(t) = \sum_{j=1}^{M} a_j(t)\cos\theta_j(t)$$

$$a_j(t) - amplitude$$

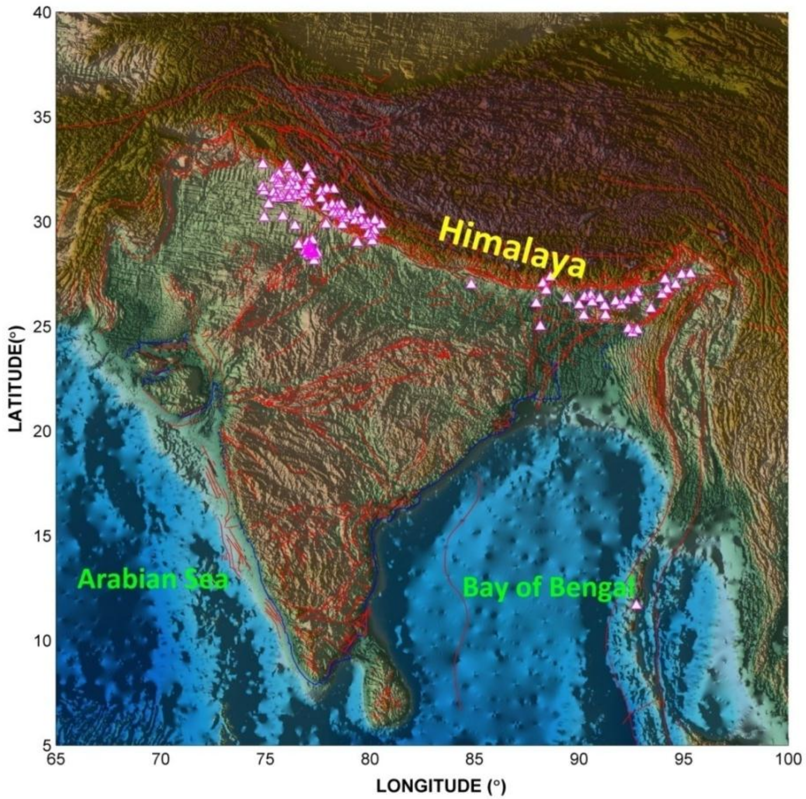
$$\theta_j(t) - Phase$$

✓Important structure like nuclear reactors, dams, reservoirs, historic structures etc.



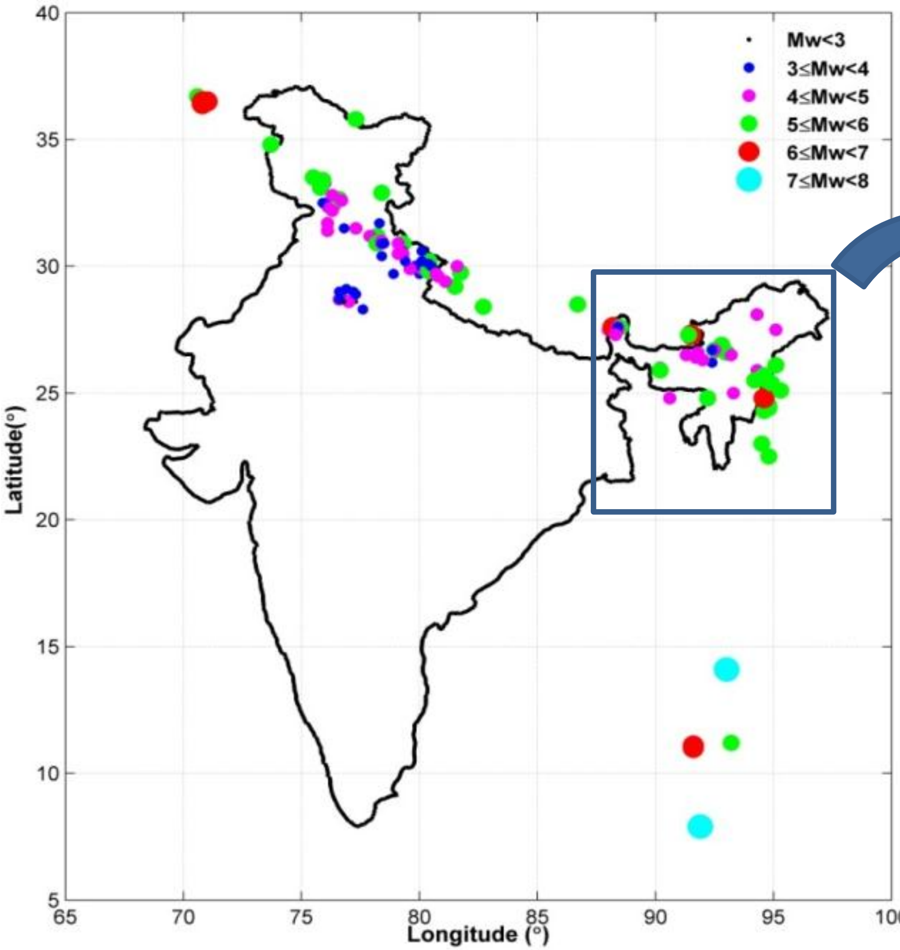
INDIAN STRONG MOTION DATABASE

- Strong motion records - Pesmos website (2005 onwards)
- Database
  - 135 earthquake events
  - 430 acceleration time histories
  - 94 recording stations
  - M_w : 2.3-7.8
  - Epicentral distance (R_{rup}) : 2-1000 km
  - Hypocentral distance (R_{rup}) : 9-1000 km
  - Focal depth (R_{rup}) : 2-190 km

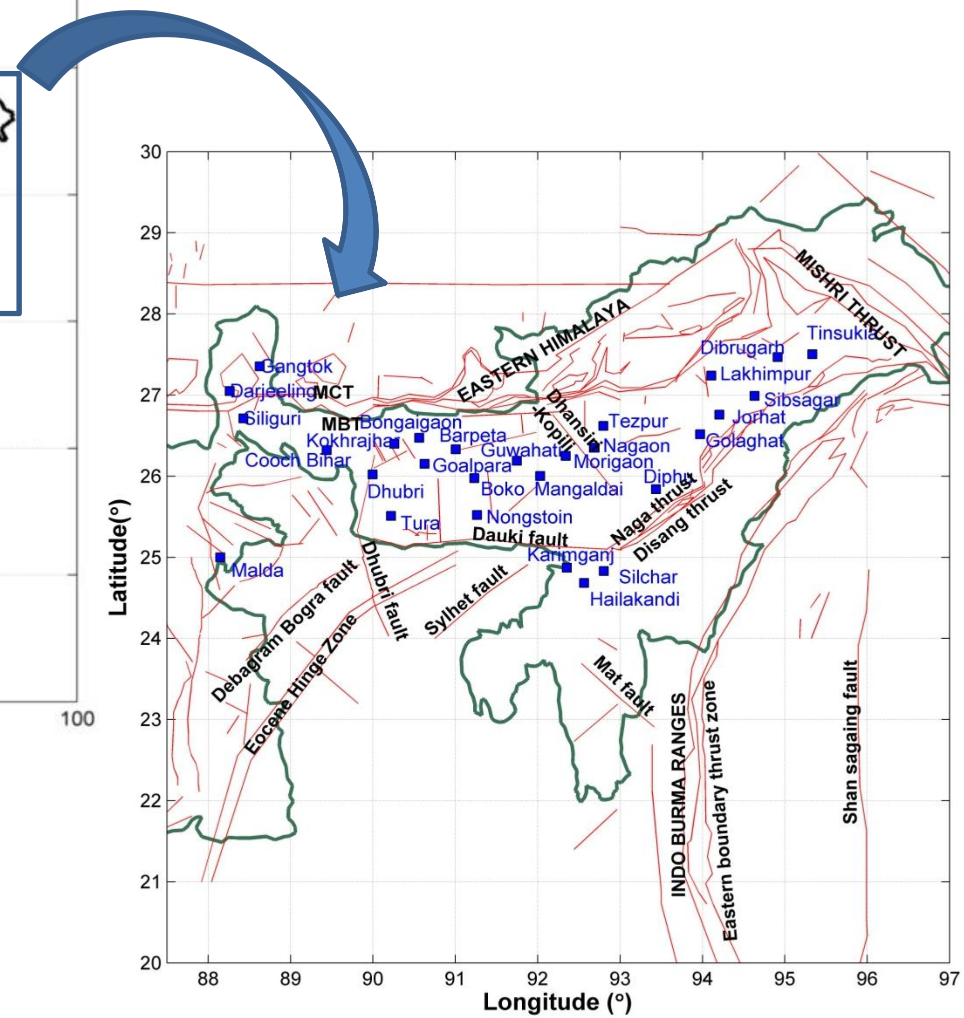


Location of the 94 strong motion station used for the present study

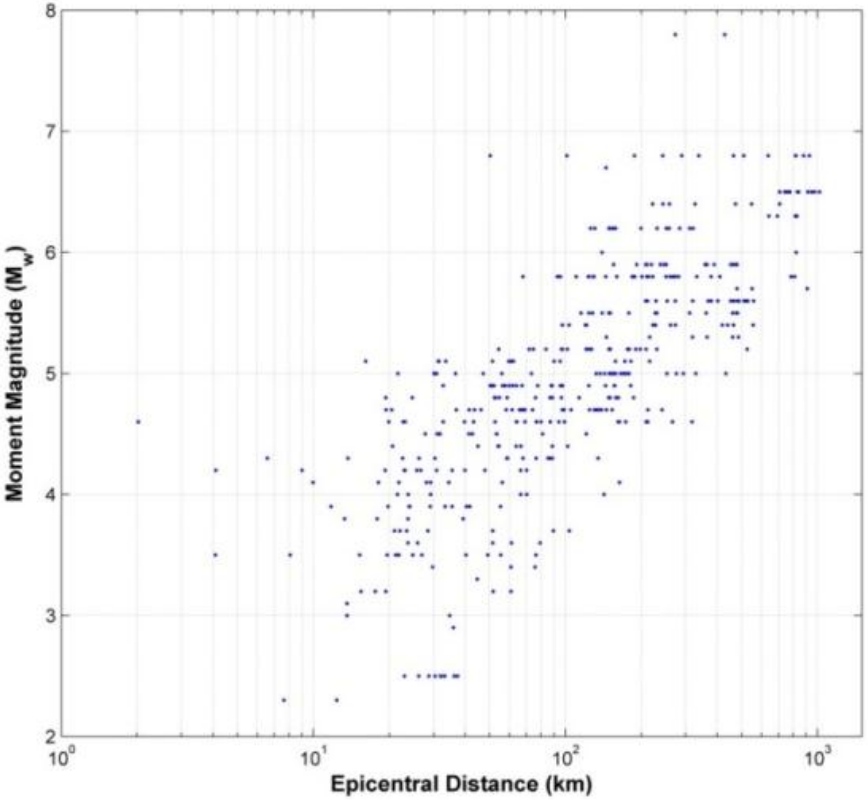
INDIAN STRONG MOTION DATABASE

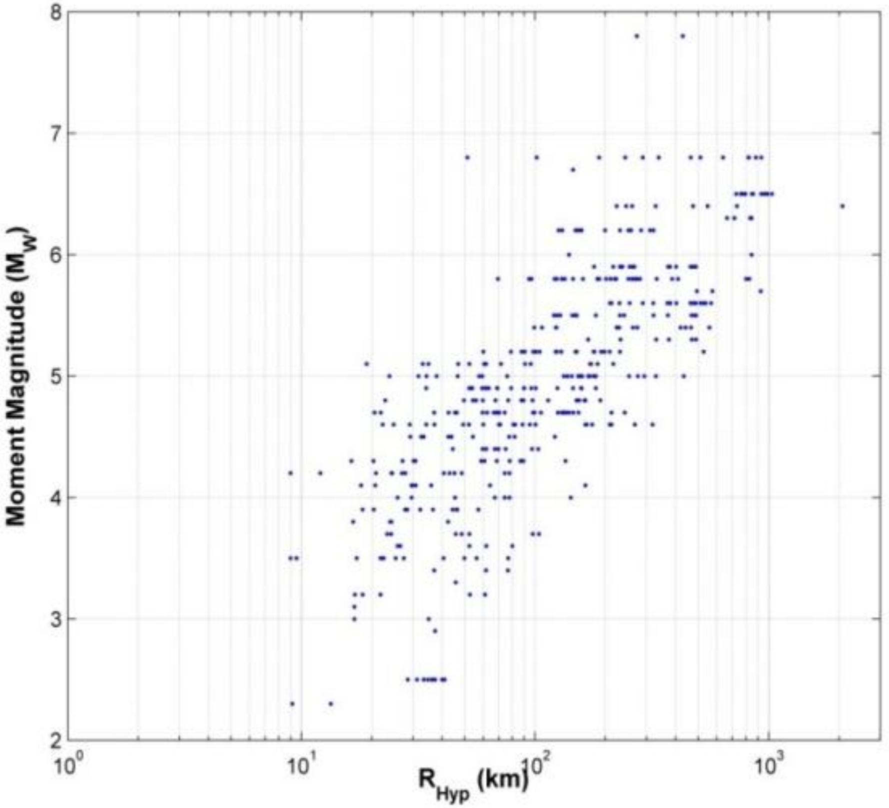


Epicenters of 135 events



INDIAN STRONG MOTION DATABASE





METHODOLOGY IN HILBERT HUANG TRANSFORM (HHT)

Hilbert-Huang Transform (HHT)

Empirical Mode Decomposition (EMD)	Hilbert Spectrum (HS)

EMPIRICAL MODE DECOMPOSITION

- Accelerograms are decomposed to Intrinsic Mode Function (IMF)
- IMF yields Instantaneous frequency as a function of time

After the EMD, the time series X(t) can be expressed in terms of IMFs as follows:

$$X(t) = \sum_{j=1}^{n} C_j(t) + r_n(t)$$

Instantaneous frequency of the j^{th} IMF is defined as

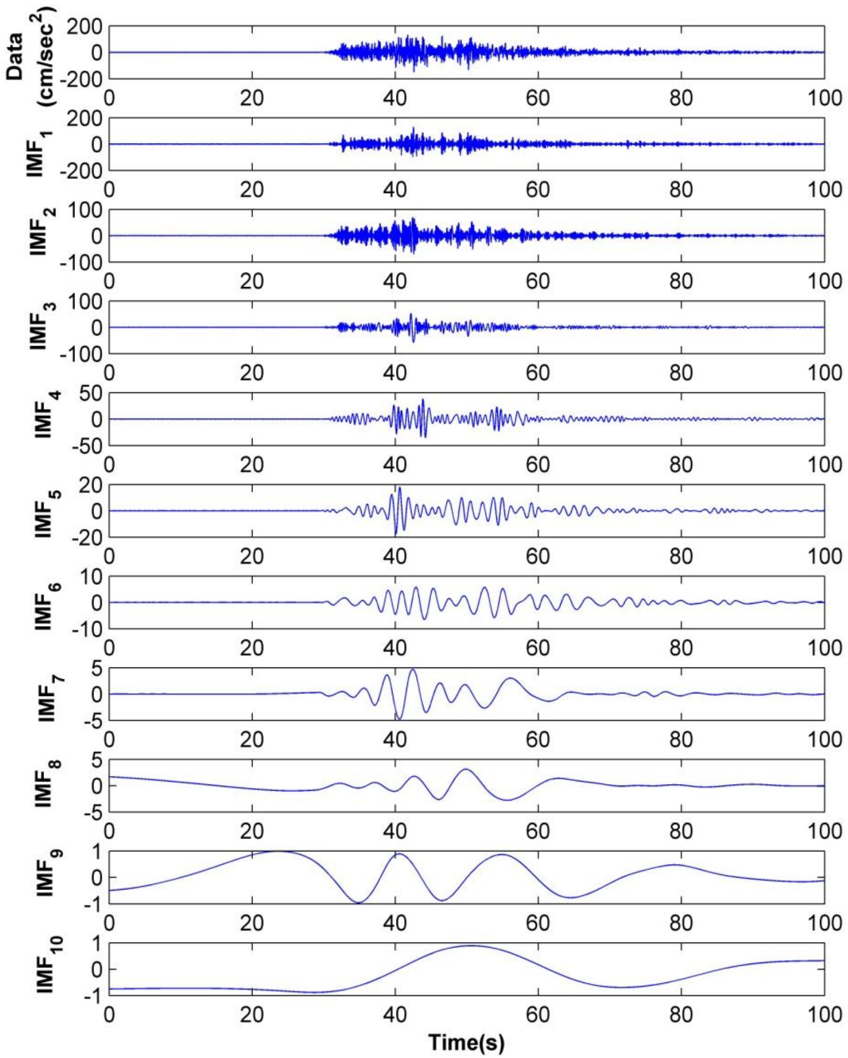
$$\omega_j(t) = d\theta_j(t) / dt$$

One can then express X(t) as follows

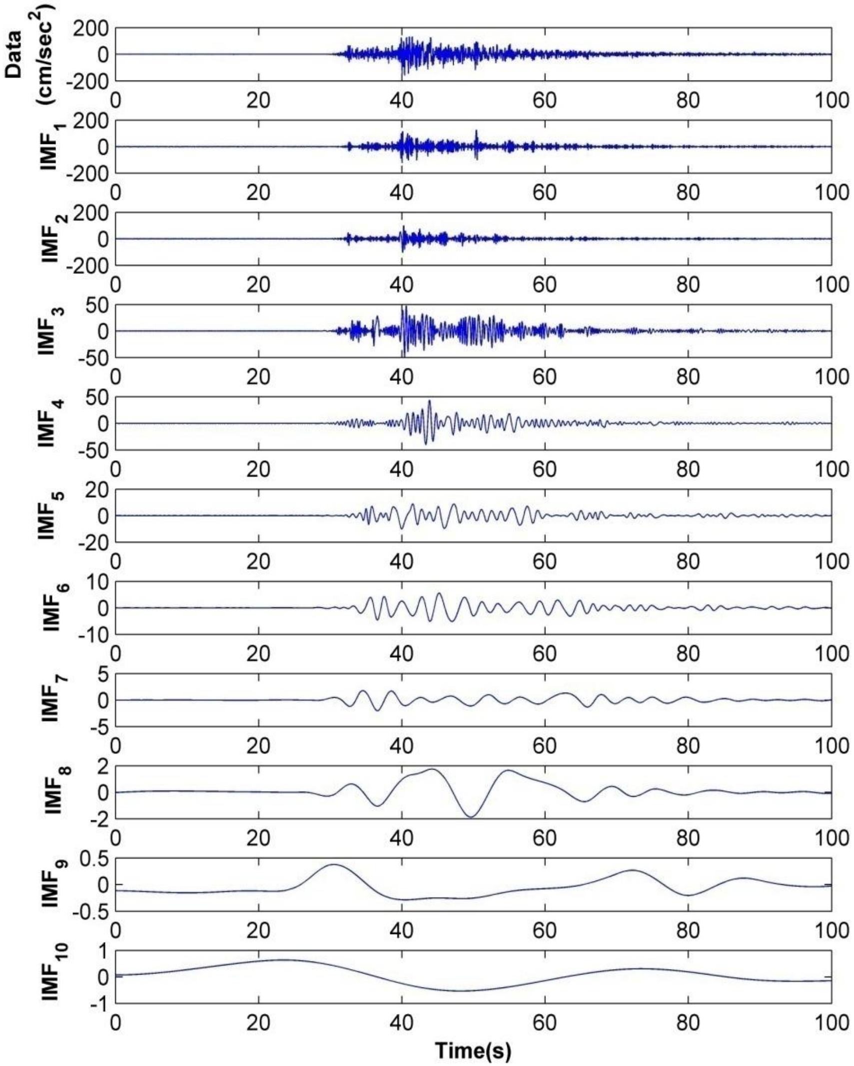
$$X(t) = \mathrm{Re}\{\sum_{j=1}^{n} a_j(t) e^{i\theta_j(t)}\} + r_n(t)$$

The instantaneous amplitude of the IMF is defined as $a_j(t)$, $r_n(t)$ is the residue and $C_j(t)$ are the IMF

IMFs OF ACCELERATION RECORDED AT GANGTOK STATION DURING SIKKIM EARTHQUAKE M_w 6.9 (18th Sept 2011)

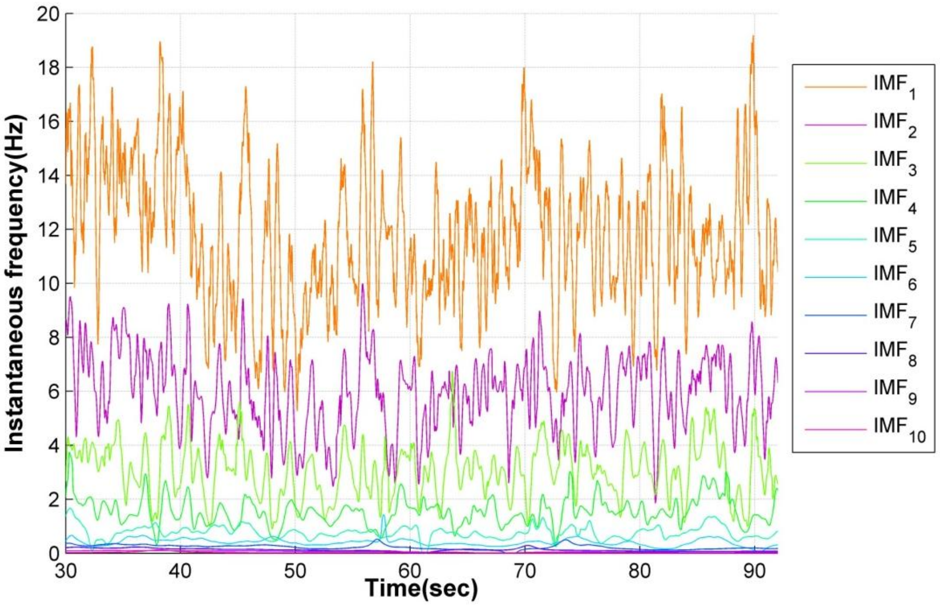


Component: EW

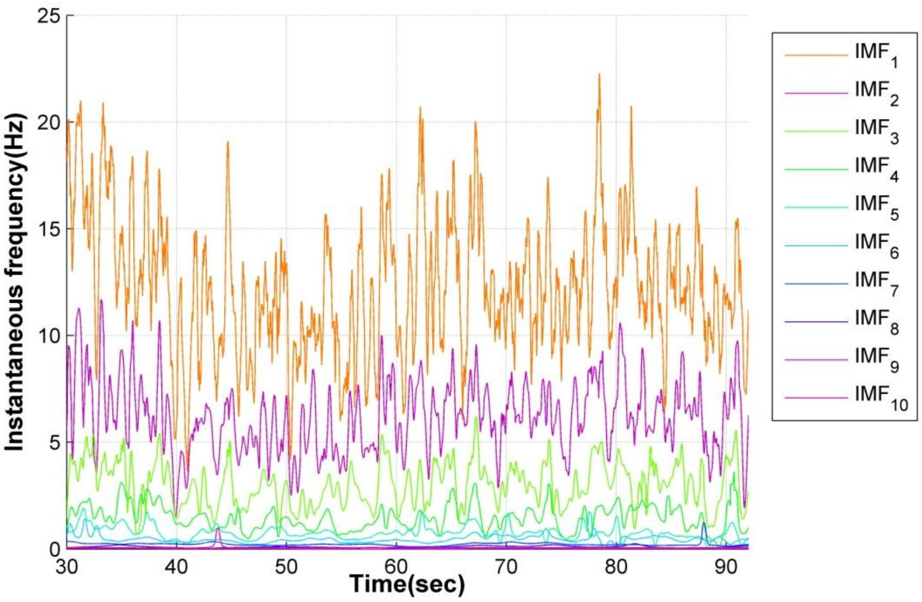


Component: NS

INSTANTANEOUS FREQUENCIES OF ACCELERATION TIME HISTORIES
STATION : GANGTOK



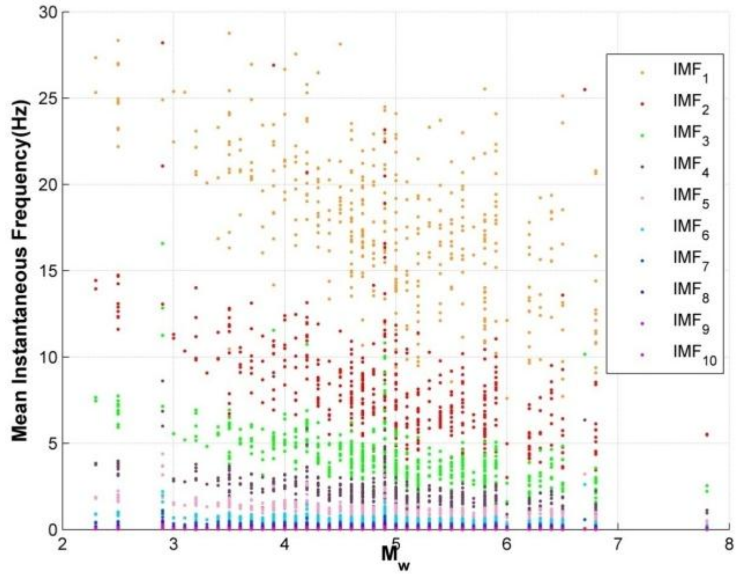
Component: EW

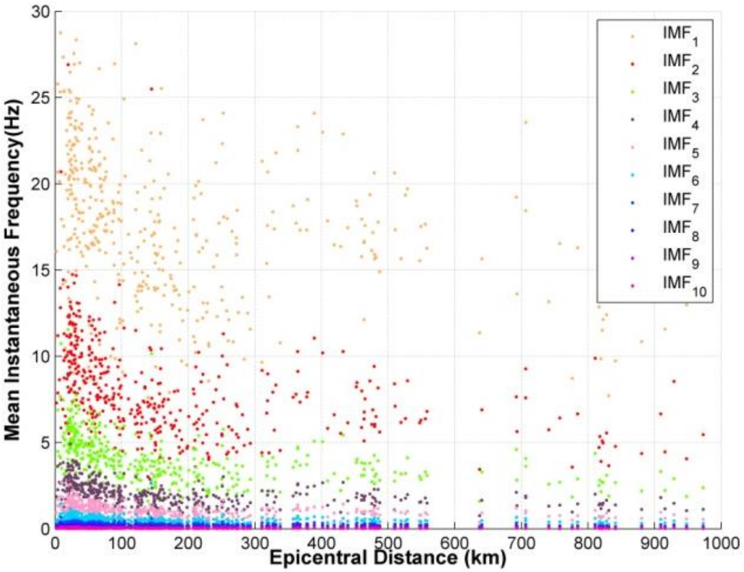


Component: NS

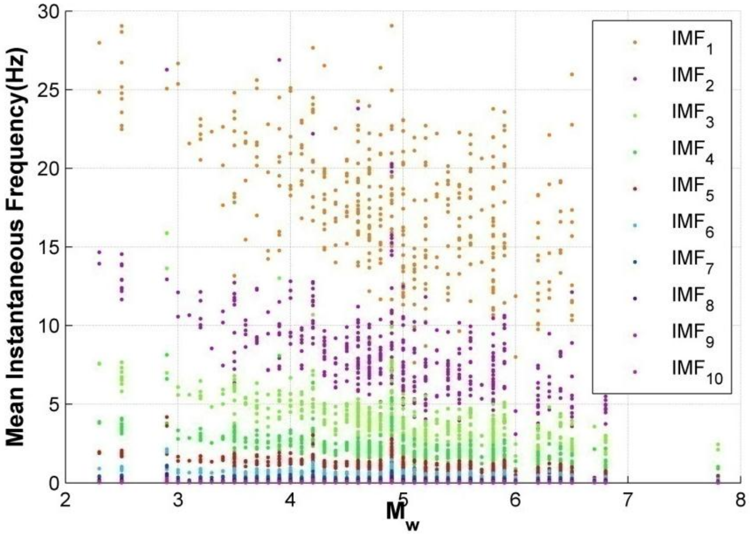
MEAN INSTANTANEOUS FREQUENCIES OF ACCELERATION TIME HISTORIES

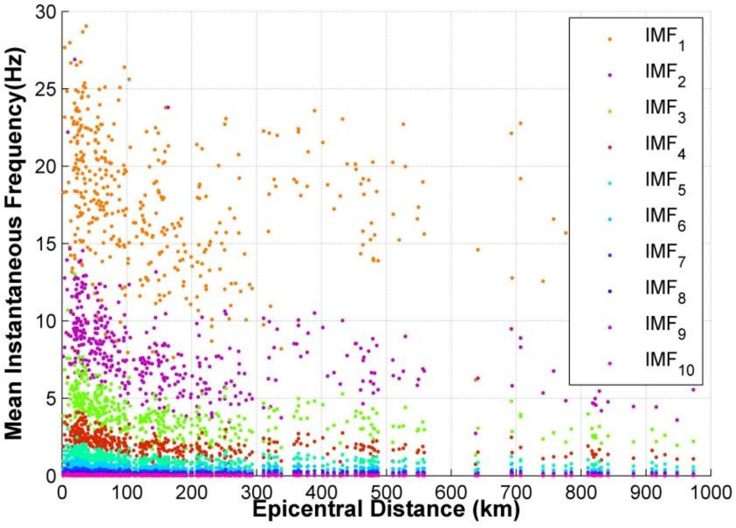
Comp: EW





Comp: NS





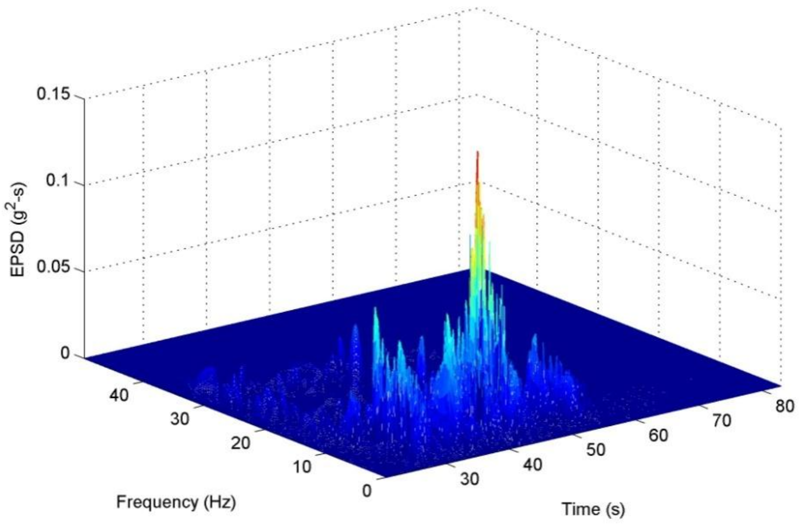
CENTRAL FREQUENCY OF THE IMF'S IN HZ AND % VARIANCE CONTRIBUTED TO TOTAL VARIABILITY OF THE DATA

	Component: EW		Component: NS	
	Frequency Mean±STD	**%Variance Explained Mean±STD**	**Frequency Mean±STD**	**%Variance Explained Mean±STD**
IMF1	18.64±6.71	42.56±21.64	18.53±6.57	42.78±22.01
IMF2	8.39±3.49	34.76±13.35	8.36±3.44	34.83±12.83
IMF3	4.23±1.71	15.62±10.77	4.19±1.70	15.46±10.45
IMF4	2.21±0.95	4.67±4.99	2.19±0.92	4.37±4.24
IMF5	1.14±0.46	1.13±1.75	1.13±0.46	1.10±1.62
IMF6	0.58±0.25	0.34±0.99	0.57±0.22	0.33±0.52
IMF7	0.28±0.11	0.12±0.13	0.28±0.11	0.14±0.22
IMF8	0.13±0.06	0.09±0.24	0.13±0.06	0.10±0.39
IMF9	0.06±0.02	0.08±0.52	0.06±0.03	0.10±0.50
IMF10	0.03±0.01	0.04±0.16	0.03±0.02	0.06±0.24

EVOLUTIONARY POWER SPECTRAL

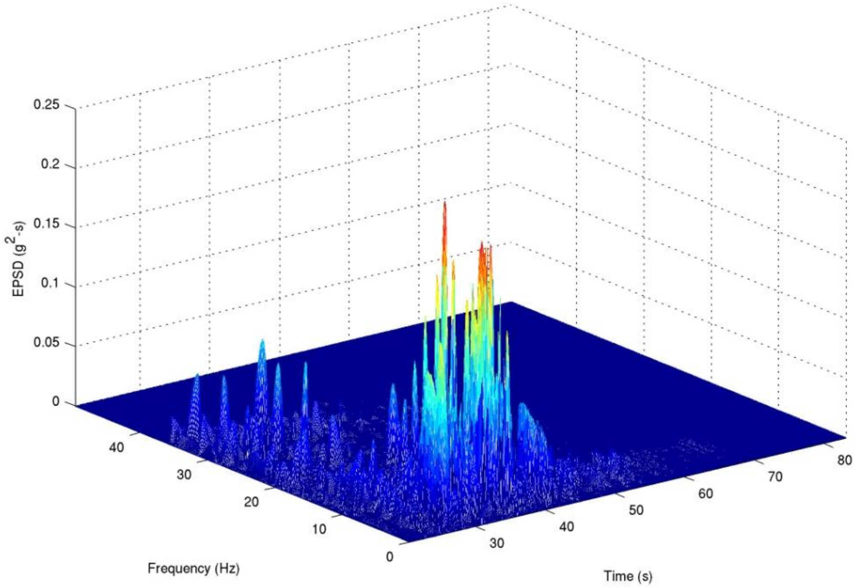
EPSD of the acceleration time history can be constructed from HHT as (Liang et al 2007).

$$G(t,\omega)=\sum_{j=1}^{n}\frac{1}{2}\delta[\omega-\omega(t)]C_j^2(t)$$



Component : EW

STATION : GANGTOK



Component : NS

STATION : GANGTOK

How to characterize the EPSD ?

SPECTRAL MOMENTS

(Raghukanth and Sangeetha ,2013)

Average instantaneous power

$$Pa(t) = \int_0^{\infty} G(t,\omega)\ d\omega$$

Central frequency

$$F_c(t) = \frac{\int_0^{\infty} \omega G(t,\omega)\ d\omega}{\int_0^{\infty} G(\tau,\omega)\ d\omega}$$

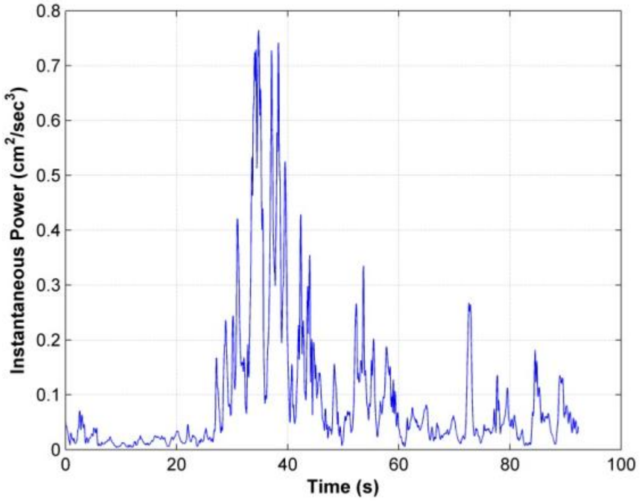
Frequency bandwidth

$$F_b(t) = \left(\frac{\int_0^{\infty} \omega^2 G(t,\omega)\ d\omega - \left(\int_0^{\infty} \omega G(t,\omega)\ d\omega \right)^2}{\int_0^{\infty} G(t,\omega)\ d\omega} \right)^{1/2}$$

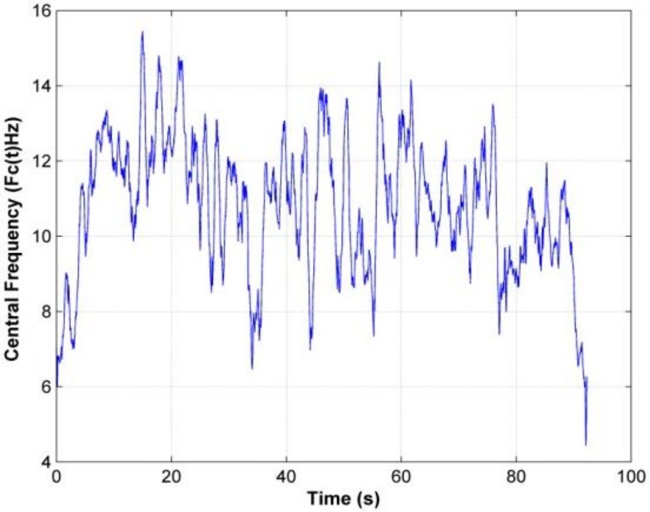
Component : EW

STATION : GANGTOK

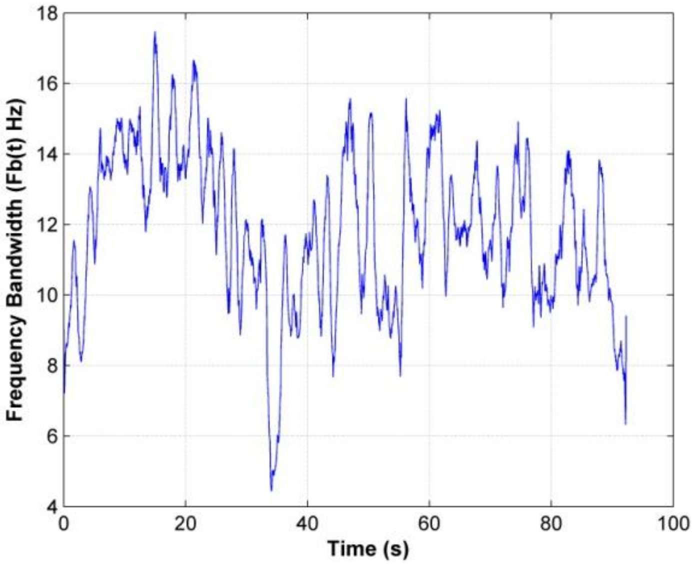
INSTANTANEOUS POWER



CENTRAL FREQUENCY



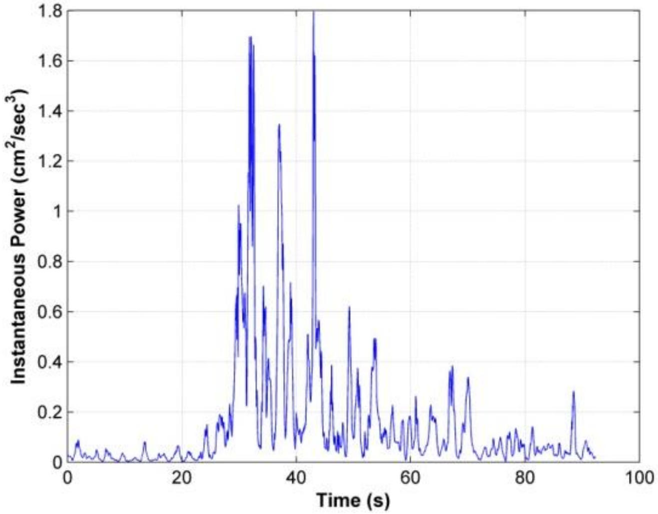
FREQUENCY BANDWIDTH



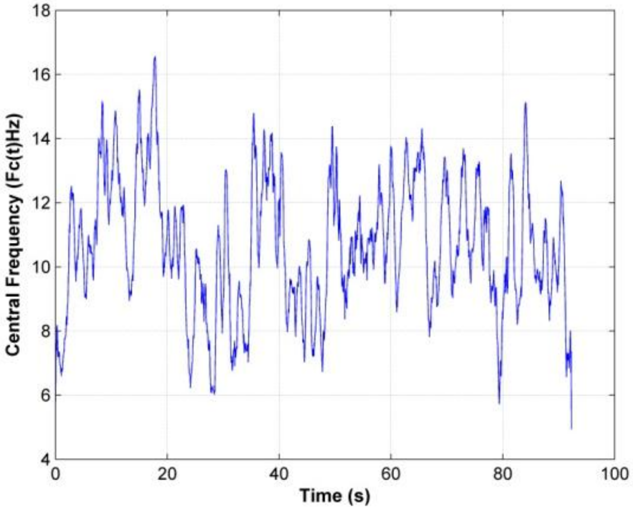
Component : NS

STATION : GANGTOK

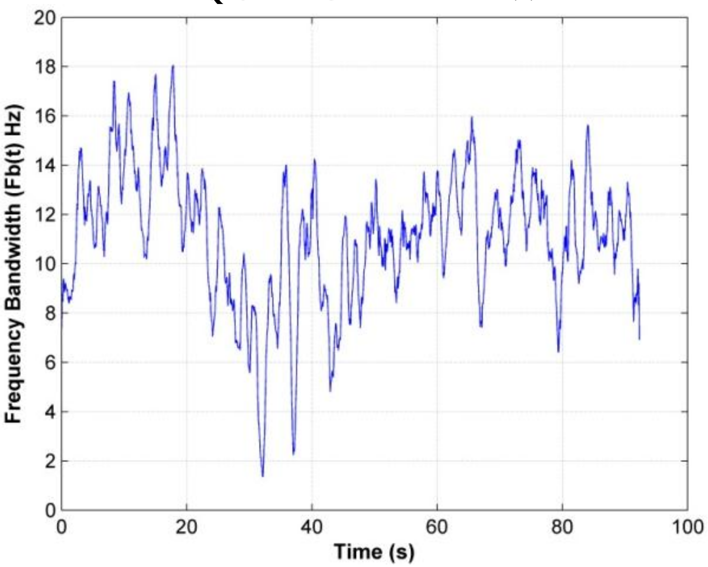
INSTANTANEOUS POWER



CENTRAL FREQUENCY



FREQUENCY BANDWIDTH



STRONG MOTION PARAMETERS

(Raghukanth and Sangeetha ,2013)

Arias Intensity

$$E_{acc} = \int_0^\infty \int_0^\infty G(t,\omega) \; d\omega dt$$

Spectral Centroid

$$E(\omega) = \frac{\int_0^\infty \int_0^\infty \omega G(t,\omega) \; d\omega dt}{\int_0^\infty \int_0^\infty G(t,\omega) \; d\omega dt}$$

Spectral Variance

$$S^2(\omega) = \frac{\int_0^\infty \int_0^\infty (\omega - E(\omega))^2 G(t,\omega) \; d\omega dt}{\int_0^\infty \int_0^\infty G(t,\omega) \; d\omega dt}$$

Temporal Centroid

$$E(t) = \frac{\int_0^\infty \int_0^\infty t G(t,\omega) \; d\omega dt}{\int_0^\infty \int_0^\infty G(t,\omega) \; d\omega dt}$$

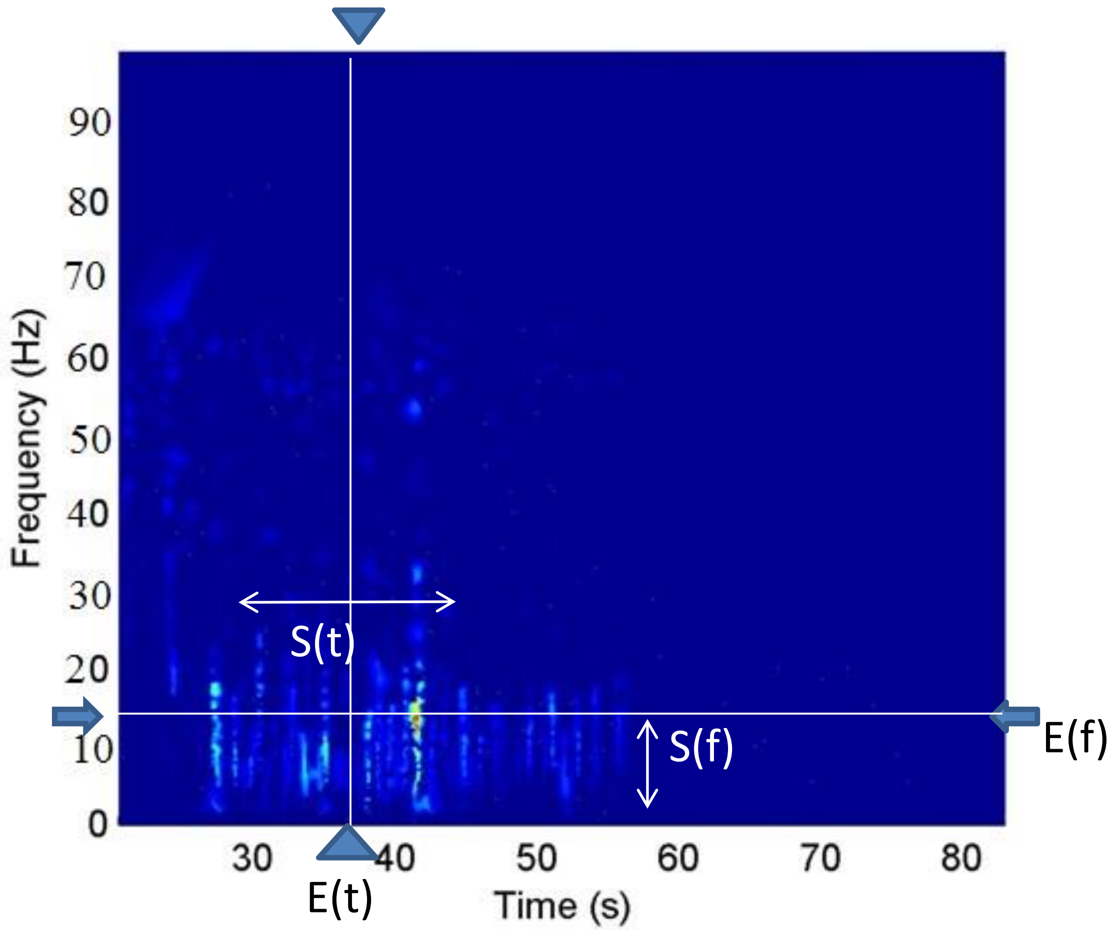
Temporal Variance

$$S^2(t) = \frac{\int_0^\infty \int_0^\infty (t - E(t))^2 G(t,\omega) \; d\omega dt}{\int_0^\infty \int_0^\infty G(t,\omega) \; d\omega dt}$$

Correlation Coefficient

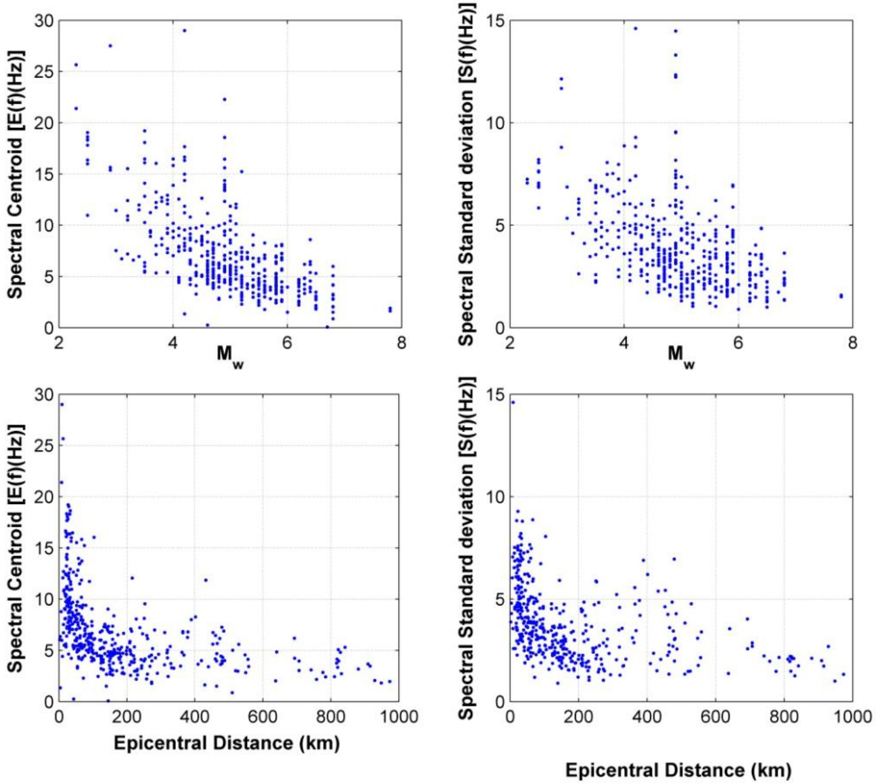
$$\rho(t,\omega) = \frac{\int_0^\infty \int_0^\infty (t - E(t))(\omega - E(\omega)) G(t,\omega) \; d\omega dt}{S(t) S(\omega) \int_0^\infty \int_0^\infty G(t,\omega) \; d\omega dt}$$

REPRESENTATION OF STRONG MOTION PARAMETERS

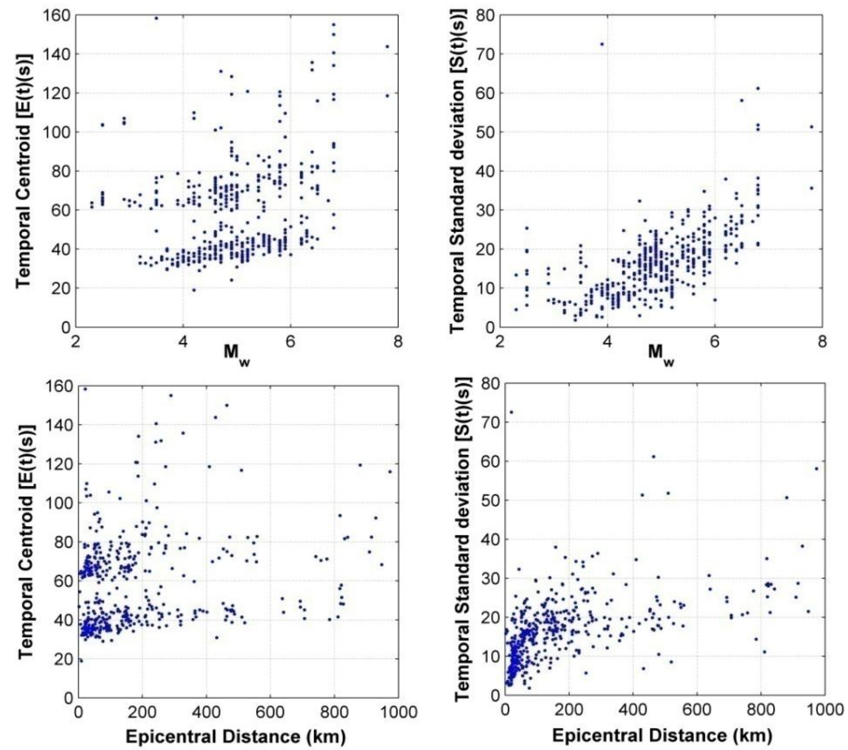


SPECTRAL/TEMPORAL CENTROID AND STANDARD DEVIATION

Comp: EW

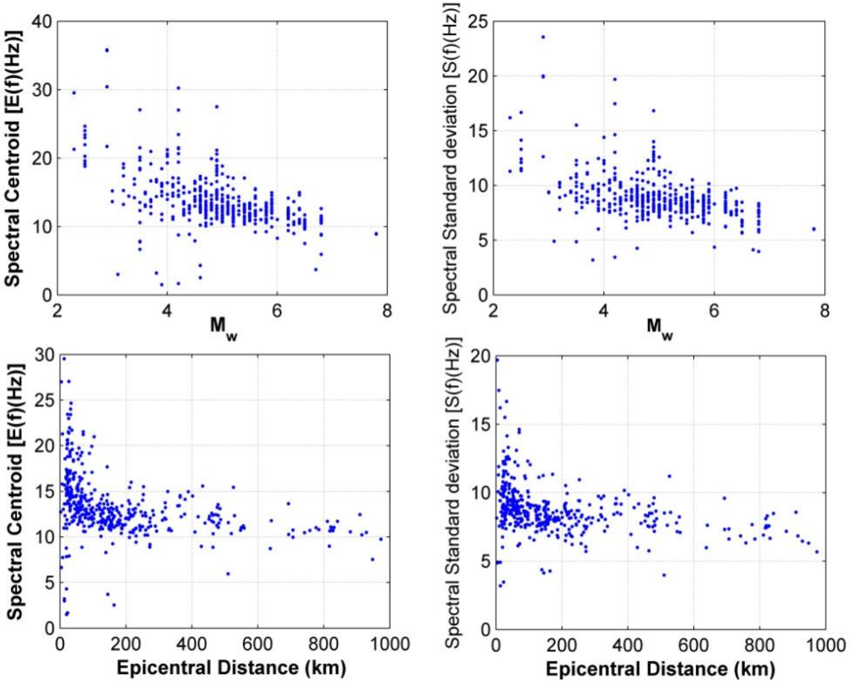


Comp: EW

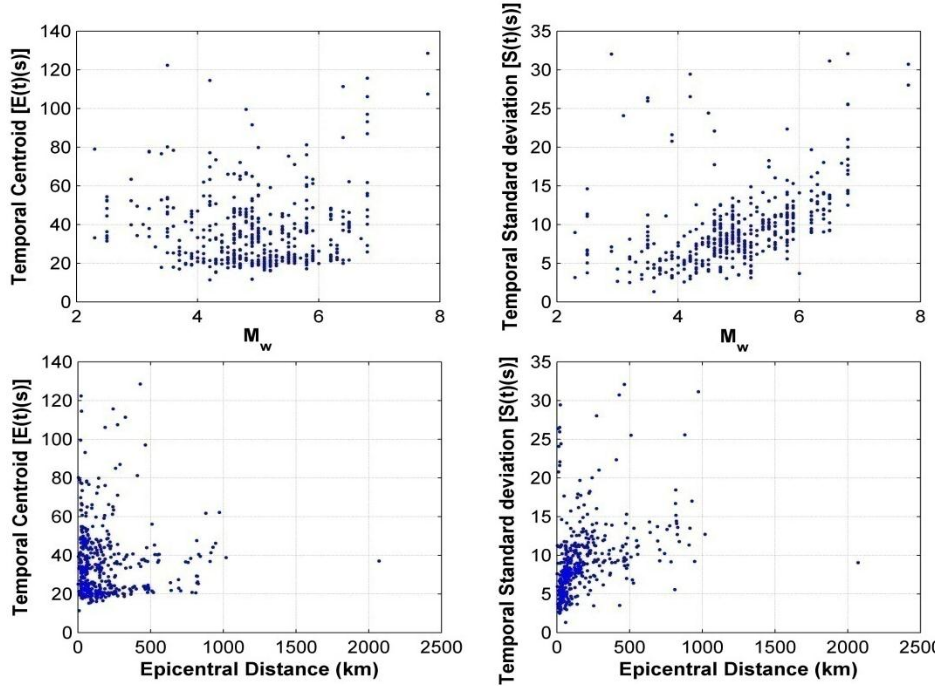


SPECTRAL/TEMPORAL CENTROID AND STANDARD DEVIATION

Comp: NS



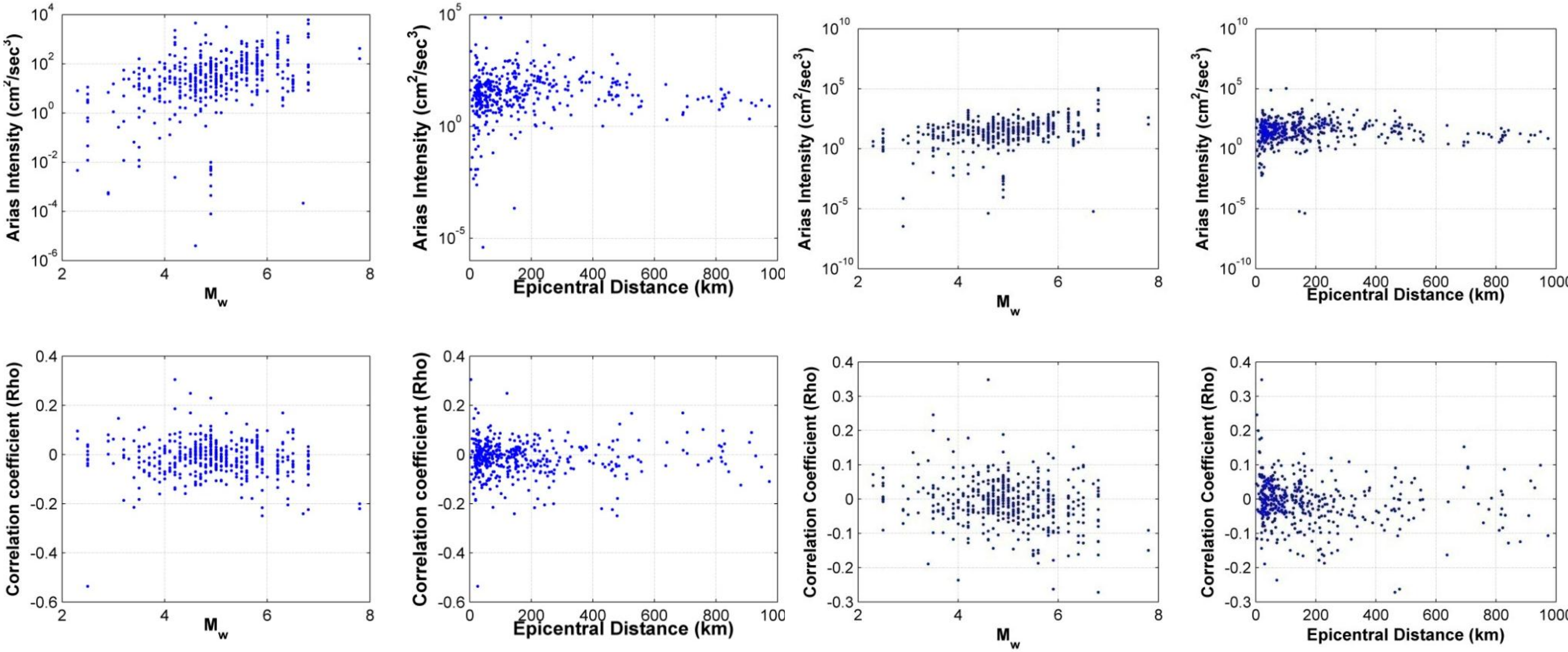
Comp: NS



ARIAS INTENSITY AND CORRELATION COEFFICIENT

Comp: EW

Comp: NS



GROUND MOTION PREDICTION EQUATIONS

Two-Stage Regression Analysis

$$ln(\mathrm{y}) = \beta_1 + \beta_2 \mathrm{M_w} + \beta_3 \ln(\mathrm{M_w}) + \beta_4 \exp(\mathrm{M_w}) + \beta_5 (\sqrt{R_{rup}^2 + h^2}) + \beta_6 ln(\sqrt{R_{rup}^2 + h^2}) + \beta_7 ln(V_{s30}) + ln(\varepsilon)$$

Where

$\beta_1, \beta_2, \beta_3, \beta_4, \beta_5, \beta_6, \beta_7$ Regression coefficients

M_w – Moment magnitude

R_{rup} –Rupture distance

V_{s30} –Shear wave velocity

y – Eacc, E(ω),S(ω),E(t),S(t), Rho

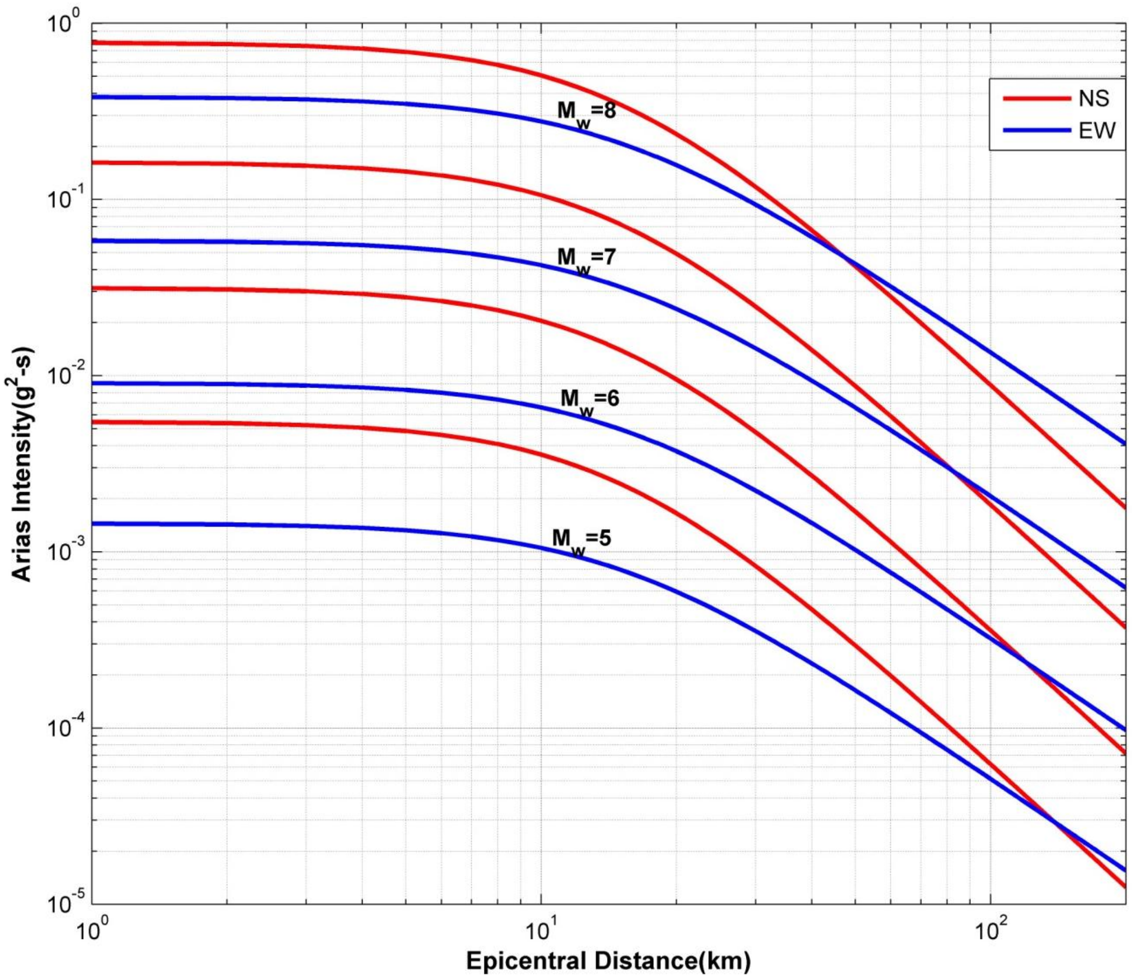
ε – Error associated with the regression

COEFFICIENTS OF THE REGRESSION ANALYSIS

Component: NS	**β1**	**β2**	**β3**	**β4**	**β5**	**β6**	**β7**	**h**	**σ(εd)**	**σ(εm)**
Eacc (cm^2/sec^3)	4.09	1.35	3.30	0.0	0	-2.76	0.003	-	1.28	2.47
E(ω) (Hz)	3.30	-0.04	0	0	-0.01	-0.13	0.02	15	0.18	0.34
S(ω) (Hz)	2.65	-0.06	0	0	-0.50	-0.05	0.02	1	0.12	0.19
E(t) (s)	3.97	0	0	0.0006	-2.40	-0.13	-0.03	1	0.29	0.36
S(t) (s)	1.05	0	0	0.0006	0.02	0.20	-0.07	11	0.25	0.41
ρ(t, ω)	0.06	-0.02	0	0	0.006	0.0006	0.02	10	0.05	0.05

Component: EW	**β1**	**β2**	**β3**	**β4**	**β5**	**β6**	**β7**	**h**	**σ(εd)**	**σ(εm)**
Eacc (cm^2/sec^3)	4.20	1.36	3.35	0.0	0	-2.8	0.004	-	1.30	2.40
E(ω) (Hz)	3.30	-0.04	0	0	-0.02	-0.13	0.02	11	0.19	0.37
S(ω) (Hz)	2.80	-0.06	0	0	-0.6	-0.06	0.03	2	0.13	0.20
E(t) (s)	4.10	0	0	0.0007	-2.5	-0.13	-0.03	3	0.30	0.37
S(t) (s)	1.20	0	0	0.0007	0.03	0.19	-0.08	10	0.25	0.42
ρ(t, ω)	0.07	-0.02	0	0	0.007	0.0006	0.03	11	0.05	0.06

GROUND MOTION RELATION FOR ARIAS INTENSITY (M_w, R & V_{s30})

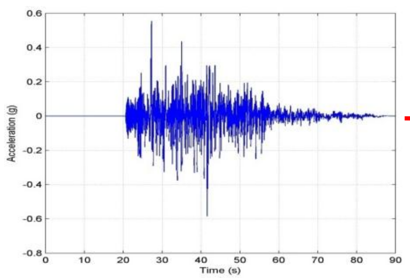


SUMMARY

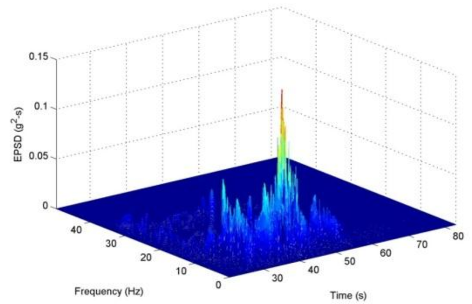
- ✓ The EMD-HHT technique for characterizing the earthquake acceleration histories has been explored.
- ✓ Earthquake accelerations can be represented as a sum of ten independent modes.
- ✓ The contribution of the individual modes to the total variability of the data has been studied. The First IMF with mean instantaneous frequency of 18 Hz explains the maximum variability (42%) of the data.
- ✓ The evolutionary power spectral density is constructed using Hilbert spectral analysis.
- ✓ Six strong motion parameters namely Arias Intensity, spectral centroid and standard deviation, temporal centroid and temporal standard deviation and correlation of frequency and time are extracted from the data.
- ✓ Empirical equations to predict these parameters are derived from the Indian strong motion database
- ✓ Given M_w, R, V_{s30} these empirical equations can be used to estimate ground motion for a future earthquake

Thank you for your kind attention

EMD Based method for simulating earthquake acceleration time histories

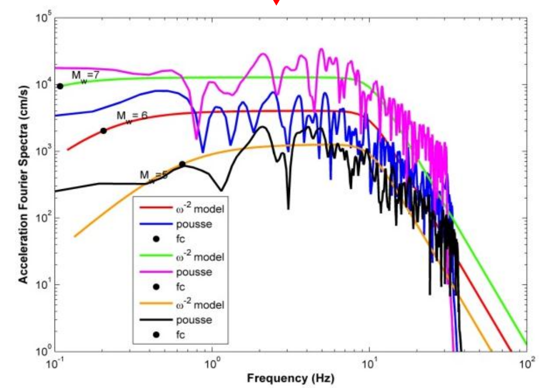


Recorded Ground Motion

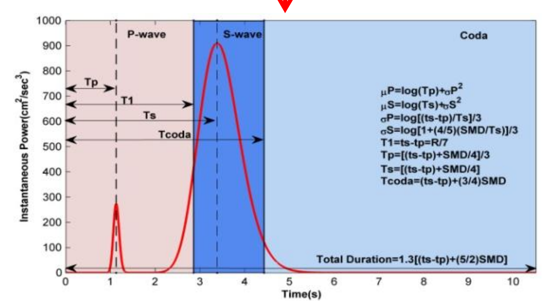


Estimated EPSD G(t, ω)

$$G(t,\omega) = G_t(\omega) Pa(t)$$



Fourier acceleration spectra $G_t(\omega)$

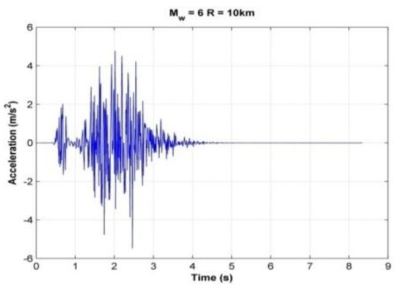


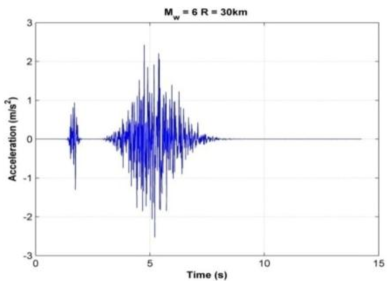
Envelope Function Pa(t)

$$a(t) = 2\sum_{n=1}^{N} C_n(t)\cos(n2\pi f_0 t + \phi_n)$$

$$C_n(t) = \sqrt{2\pi f_0 G(t,\omega)}$$

Time-history simulation





Simulated Ground Motion