Relevance and Possibility of EEW System in Northern India

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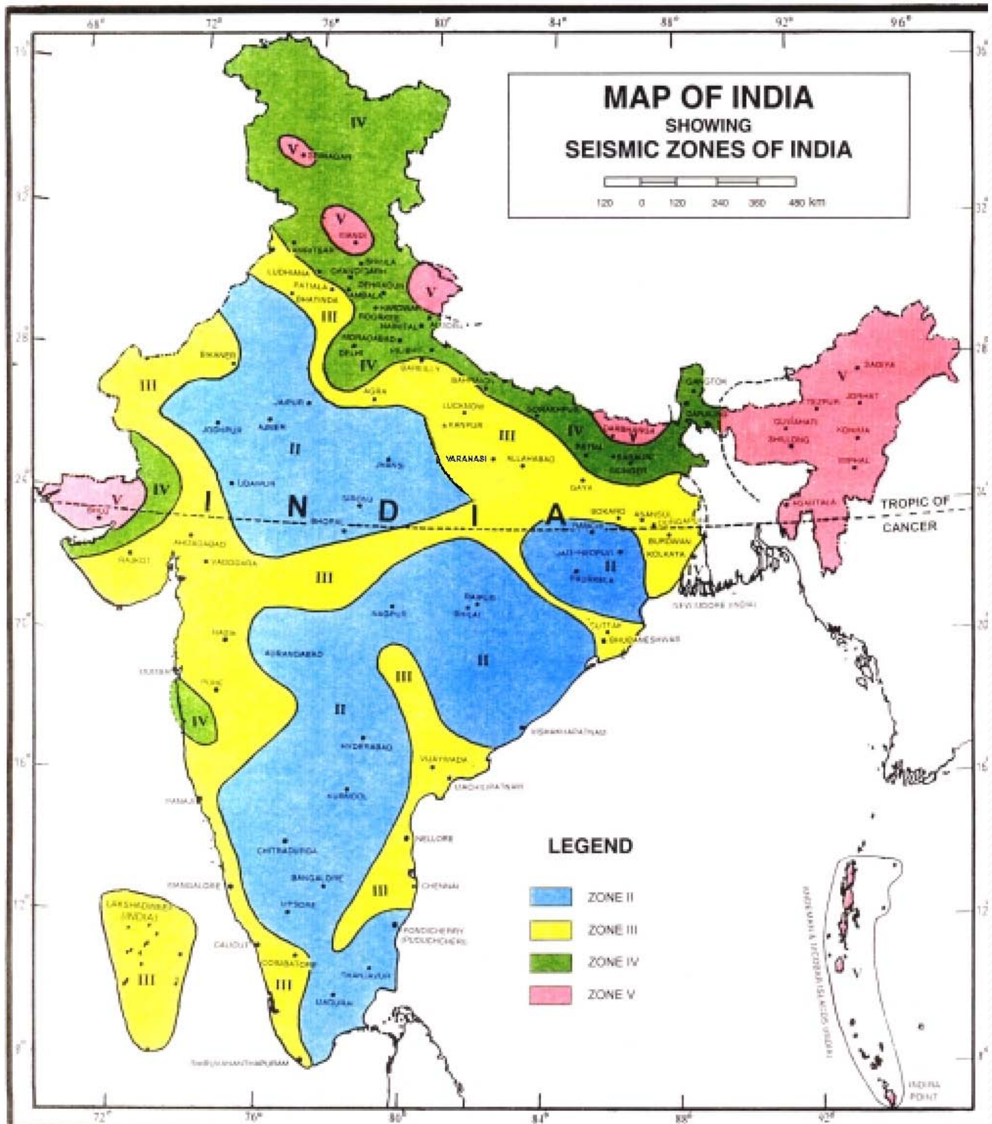
Physical Basis of Earthquake Early Warning

- Strong ground shaking , damage to structures and casualty are caused by shear-waves and by the subsequent surface waves
- Shear waves travel at about half the speed of the primary waves
- All elastic waves travel much slower than electromagnetic signals transmitted wireless or through cables.
- Thus, depending on the distance of epicentre from the endangered urban area, transmission of information and real-time analysis of the first primary wave may provide warnings from few seconds to a few tens of seconds before the arrival of strong ground shaking.

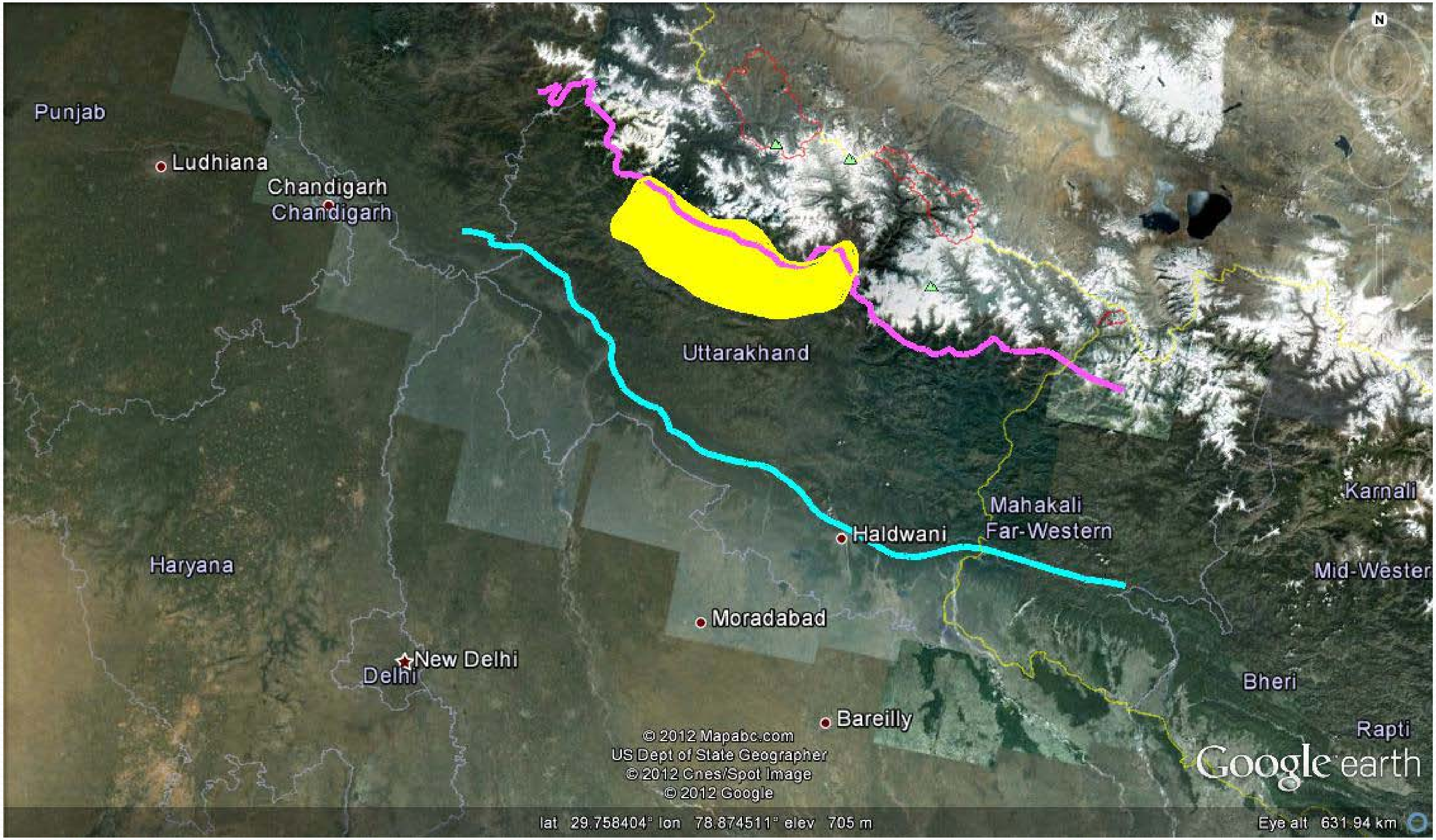
Seismic Zoning Map of India



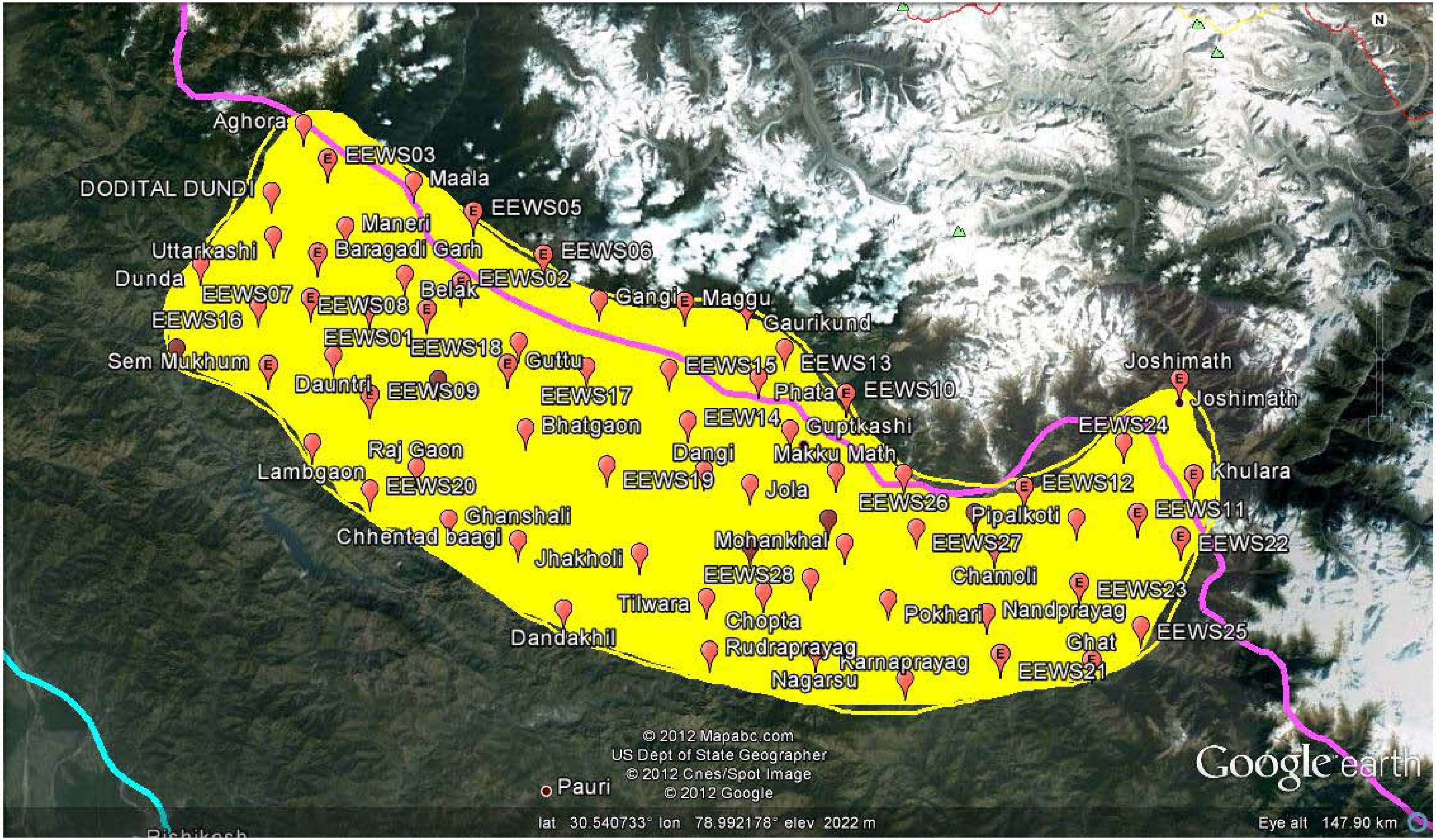
EEW for Northern India

- Possibility of large size earthquake in seismic gap of Indian Himalayas
- Can effect several cities (including Delhi) and several industrial hubs
- Large population density at 100 to 300 Km from this region
- Lead time of 25 to 80 seconds may be available at these places
- Thus EEW is most relevant for Northern India

Region Identified for EEW Instrumentation



Proposed Location of Sensors



Segments of EEW

EEW comprises of

- Field Instruments (As close as possible)
  - Location and placement
  - Capability to record strong ground motion
  - Capability of real time streaming
  - GPS timing
  - Low power requirement
- Connectivity of all field stations to HQ
  - Preferably dedicated satellite channels
  - Other options: leased lines or VSAT

Segments of EEW

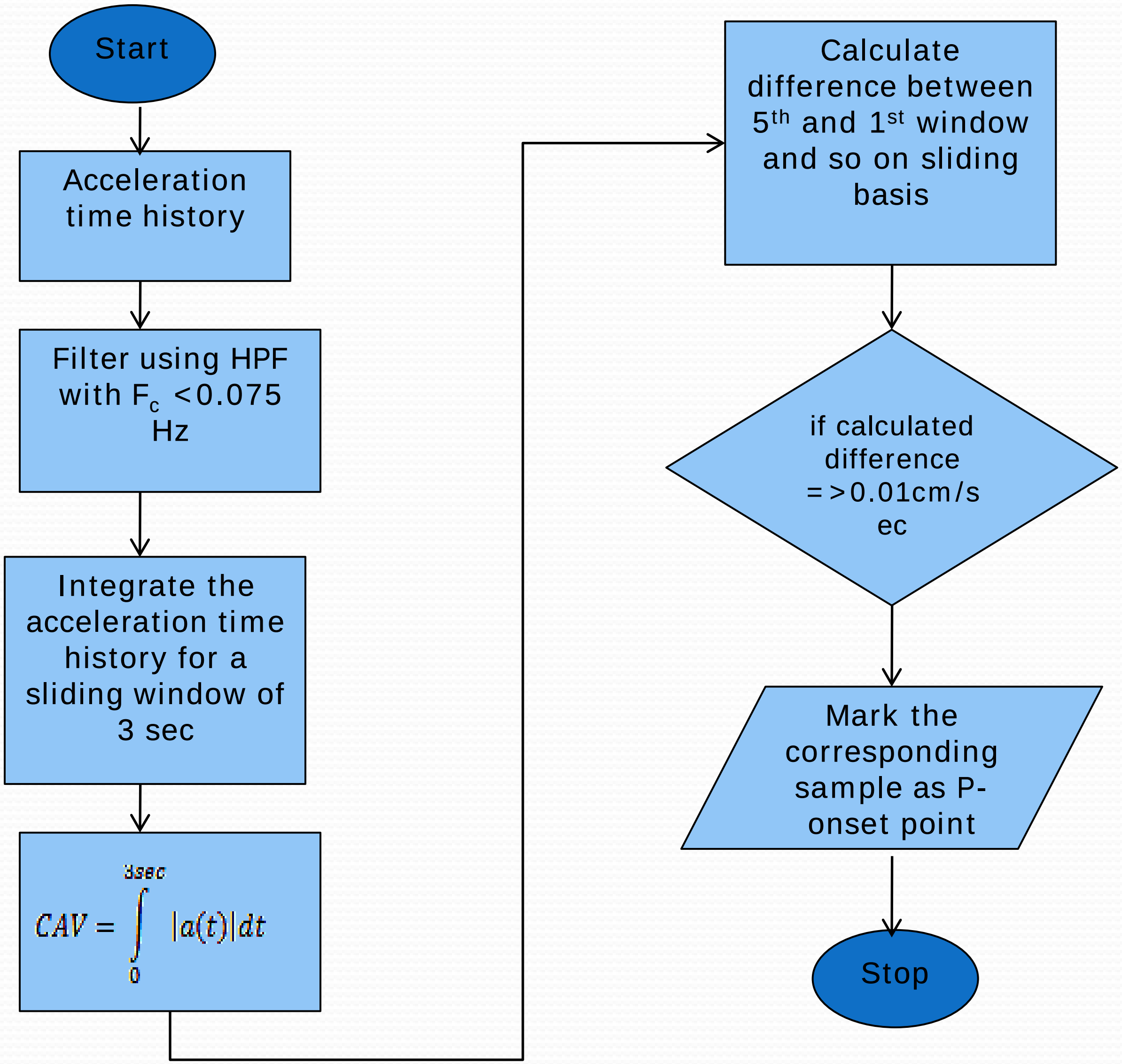
- Receiver and Computation at HQ
  - Very high speed computational facility
  - Real time software to detect onset of P wave arrival
  - Real time software for calculations of attributes in first few seconds of onset
    - Cumulative absolute velocity(CAV)
    - Determination of τ_c
    - Root squared sum cumulative velocity(RSSCV)
    - Predominant period
    - Algorithm based on assigned votes of attributes for issue of various stages of warning

Segments of EEW

- Develop Protocol for Issuing Warning
  - Provide trigger to industry
    - Shut down
    - Halt some activities
    - Several other use which we do not know
  - Warning broadcasted to TV / Radio Stations
  - Warning issued through automatic ringing of mobile phones

Algorithms for Earthquake Early Warning

Algorithm for Automatic P-onset Detection



Cumulative Absolute Velocity (CAV)

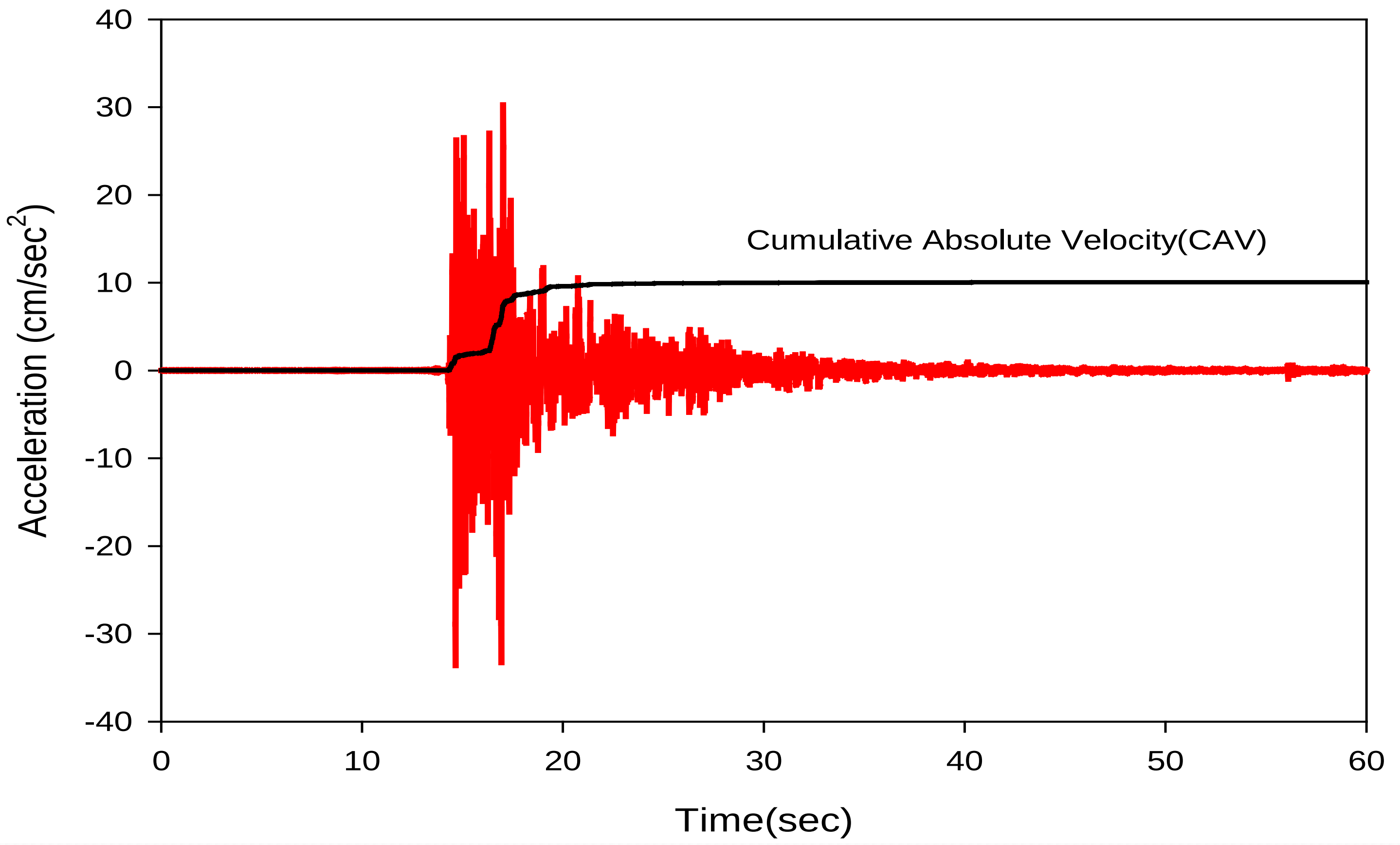
- CAV was developed by Kennedy and Reed in a study sponsored by EPRI, Palo Alto in1988 for application in NPI
- Mathematically

$$CAV = \int_0^{t_{max}} |a(t)|\,dt$$ (EPRI 1988)

Where, t_{max} is the total duration of time series

- It is a parameter for determining the damage threshold for nuclear plants and industrial grade equipment subjected to earthquake ground motion

A Typical Variation of CAV for M=5,FD=10 and Δ < 5 km



Threshold Determination using CAV

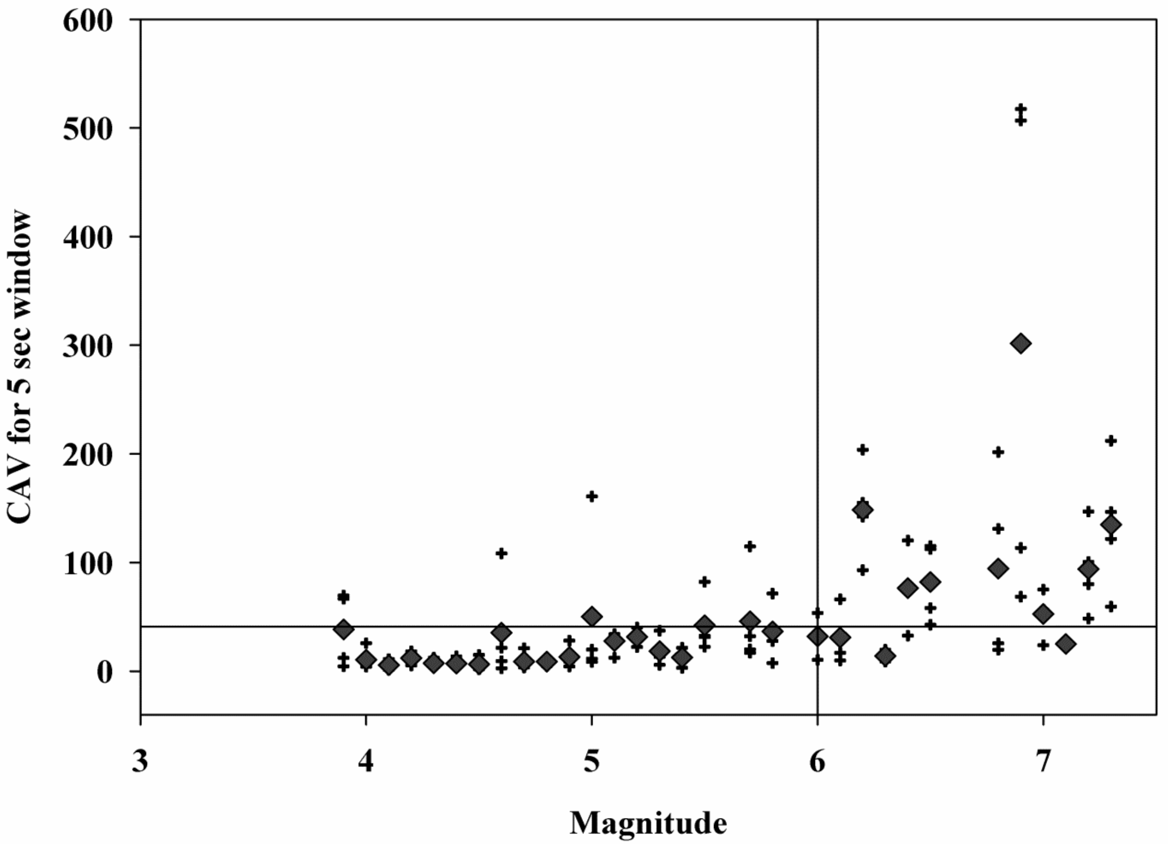
- After detection of P-onset point, now CAV approach has been used to find out the threshold at which warning can be issued.

- Thus on calculating the maximum value of CAV for 5 sec window after P-onset detection it is found that for epicentral distance of 50 km. predefined threshold give good results.

Strong Motion Database For EEW Threshold

- For analysis in (Graph-1) 113 K-NET strong motion records has been taken with epicentral distance less than 50 km and magnitude range (3.9-7.3).

Graph-1 for Epicentral Distance of 50 km



- From Graph it has been found that for epicentral distance of 50 km only three missed alarms are there for magnitude >6 . Out of these three, two are such earthquakes where data is available from one station only.

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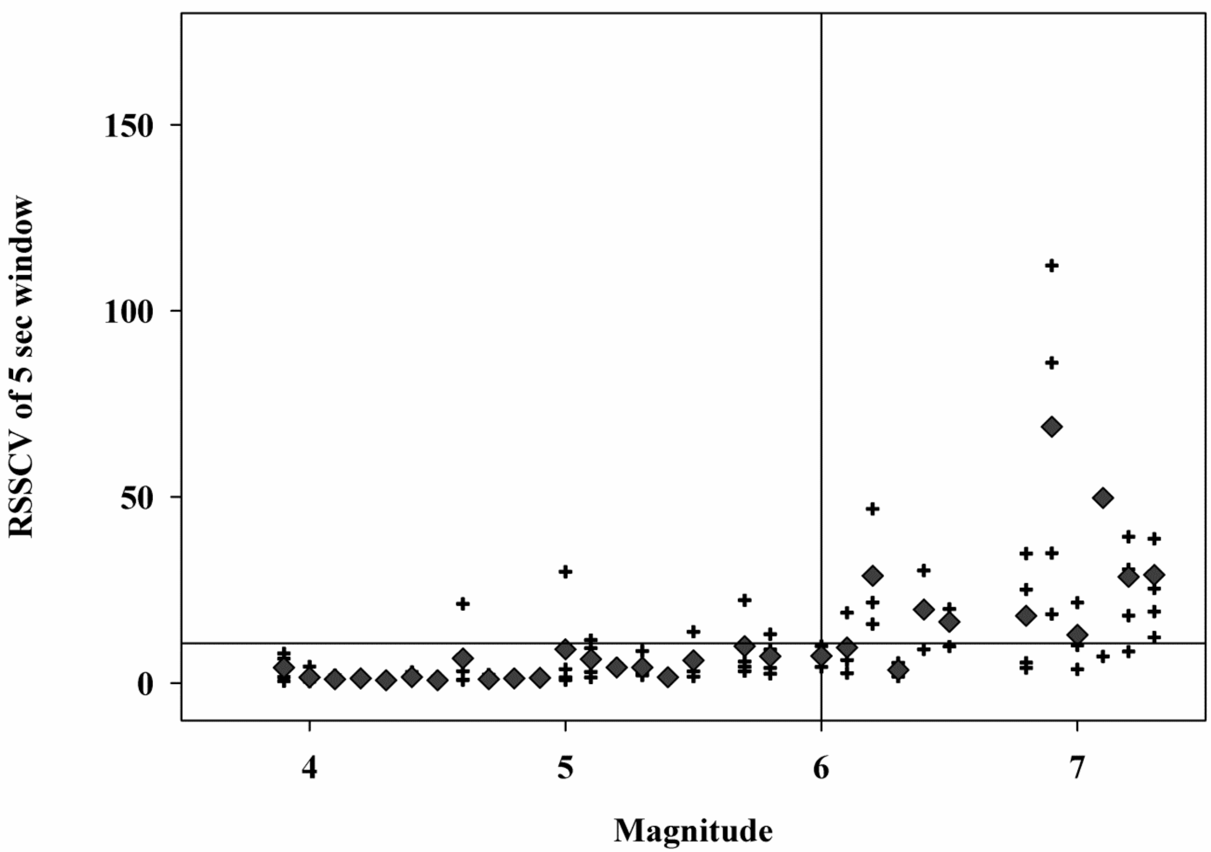
RSSCV

$$RSSCV = \sqrt{\sum_{i=1}^{n} v_i^2}$$

- where, v_i is the velocity vector calculated by integrating the acceleration time series for the number of samples in the selected window (1 to n) and n is the number of samples in the selected window. The CAV and RSSCV include the cumulative effects (amplitude and time) of ground motion duration.

RSSCV for Epicentral Distance of 50 km



- From Graph it has been found that for epicentral distance of 50 km only one missed alarm is there for magnitude >6 . This one missed alarm is for such earthquake where data is available from one station only.

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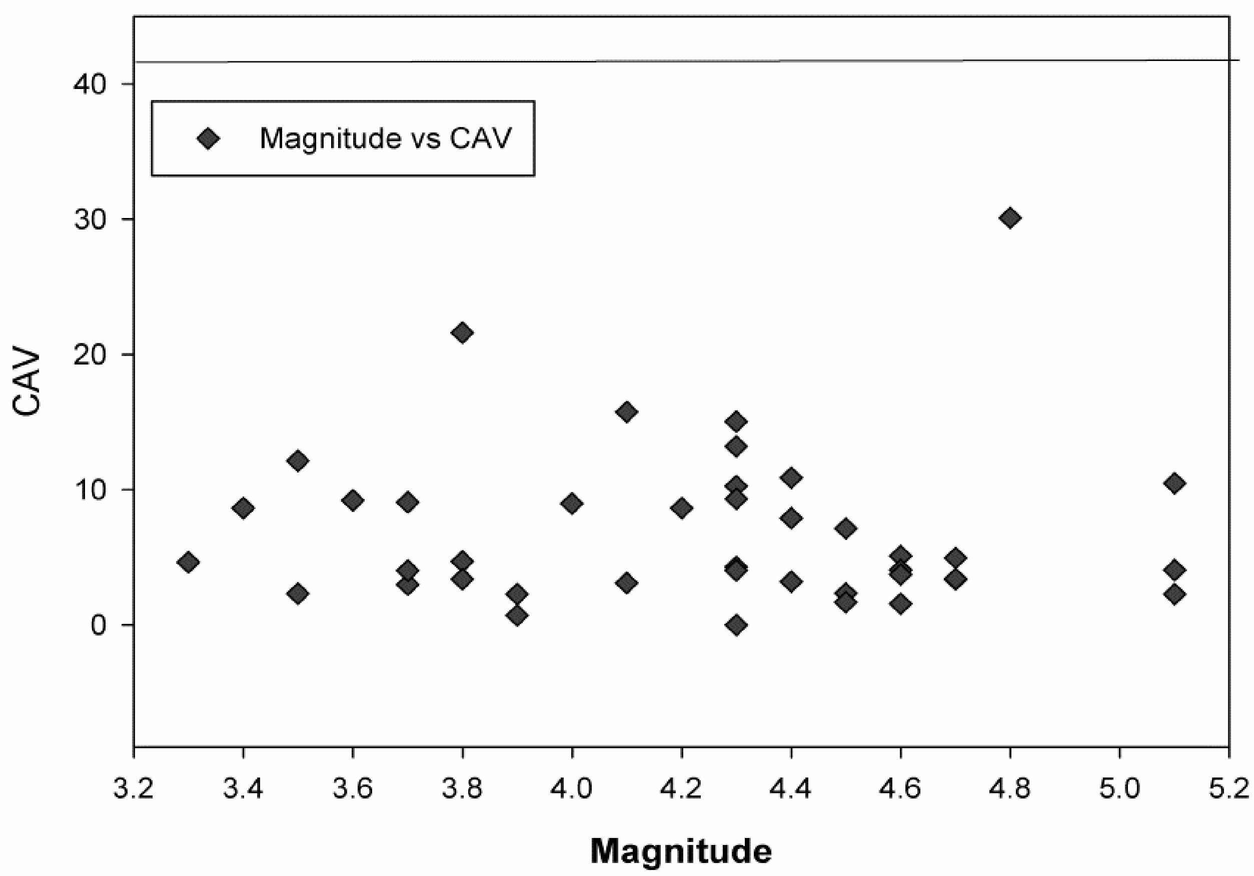
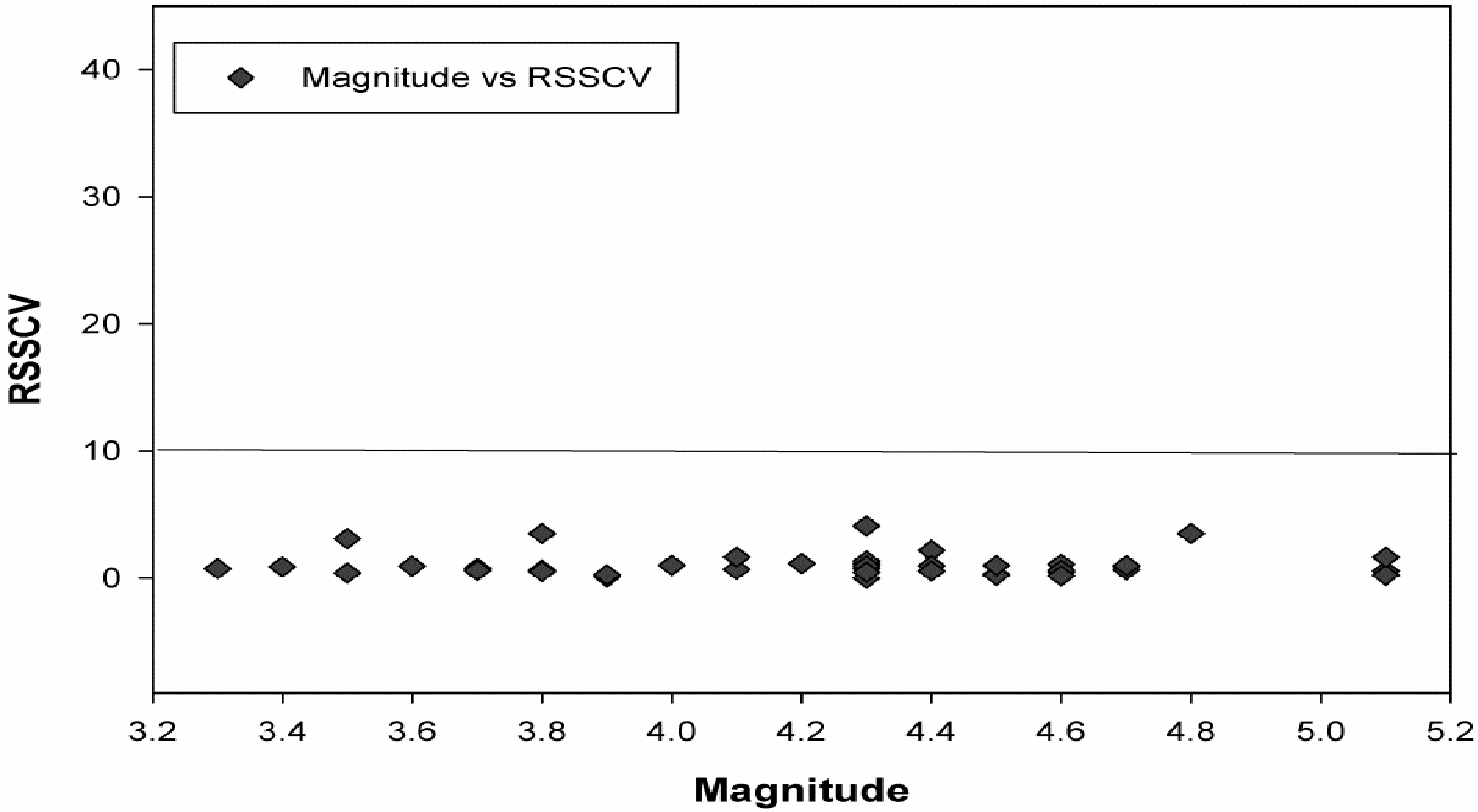
Contd..

- Thus, it has been found that at a CAV threshold of 41 cm/sec an EEW can be issued.
- This approach has also been used by Hakan Alcik for issuing three level alarm system Marmara region.

CAV for Indian Data



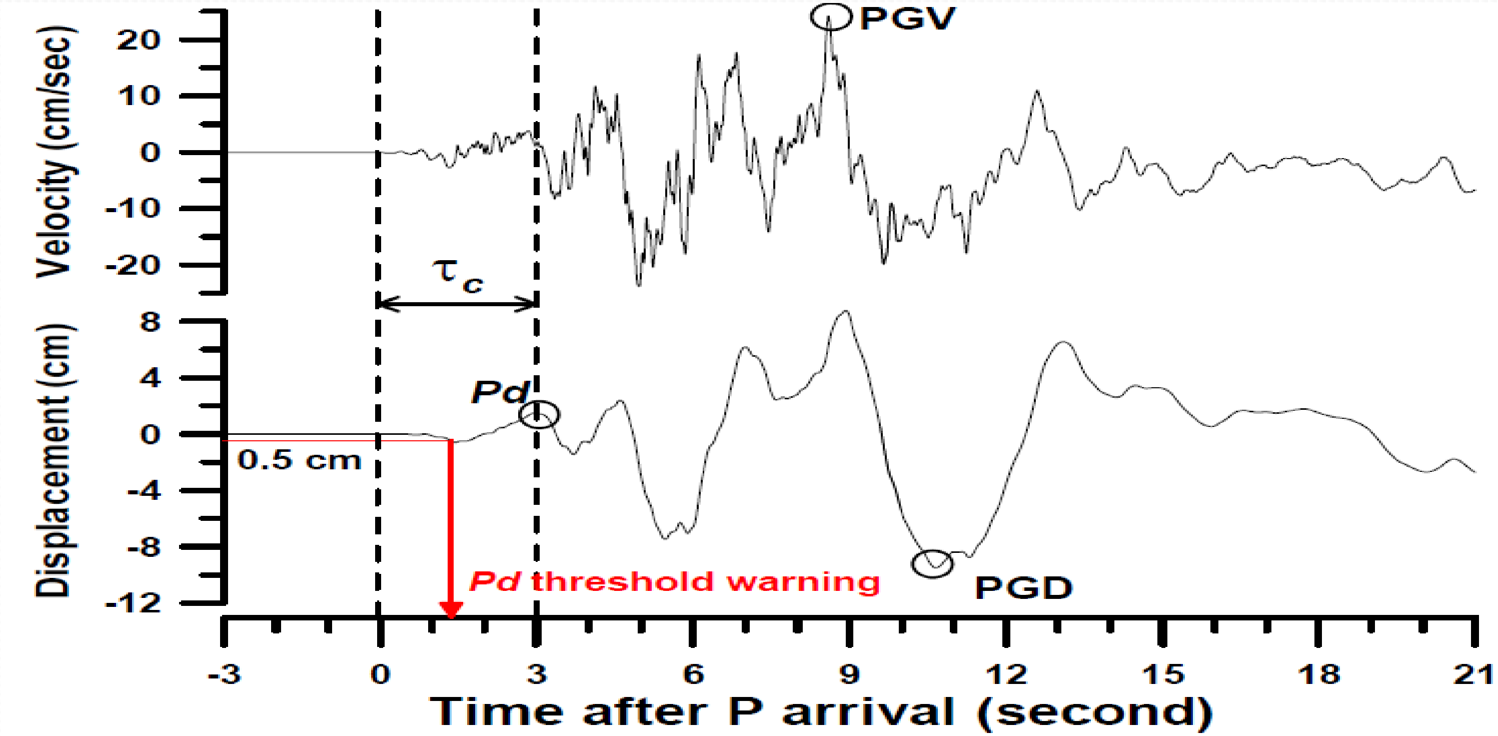
RSSCV for Indian dataset



Proposed Methodology (to be studied for Indian Context)

τ_c –Pd method

In this method τ_c (ground motion period parameter) and P_d (a high pass filter vertical displacement amplitude parameter) from the initial 3s of P-wave calculates magnitude and PGV.



τ_c

- The period parameter τc, from the initial 3 sec of P waves. τc is determined as

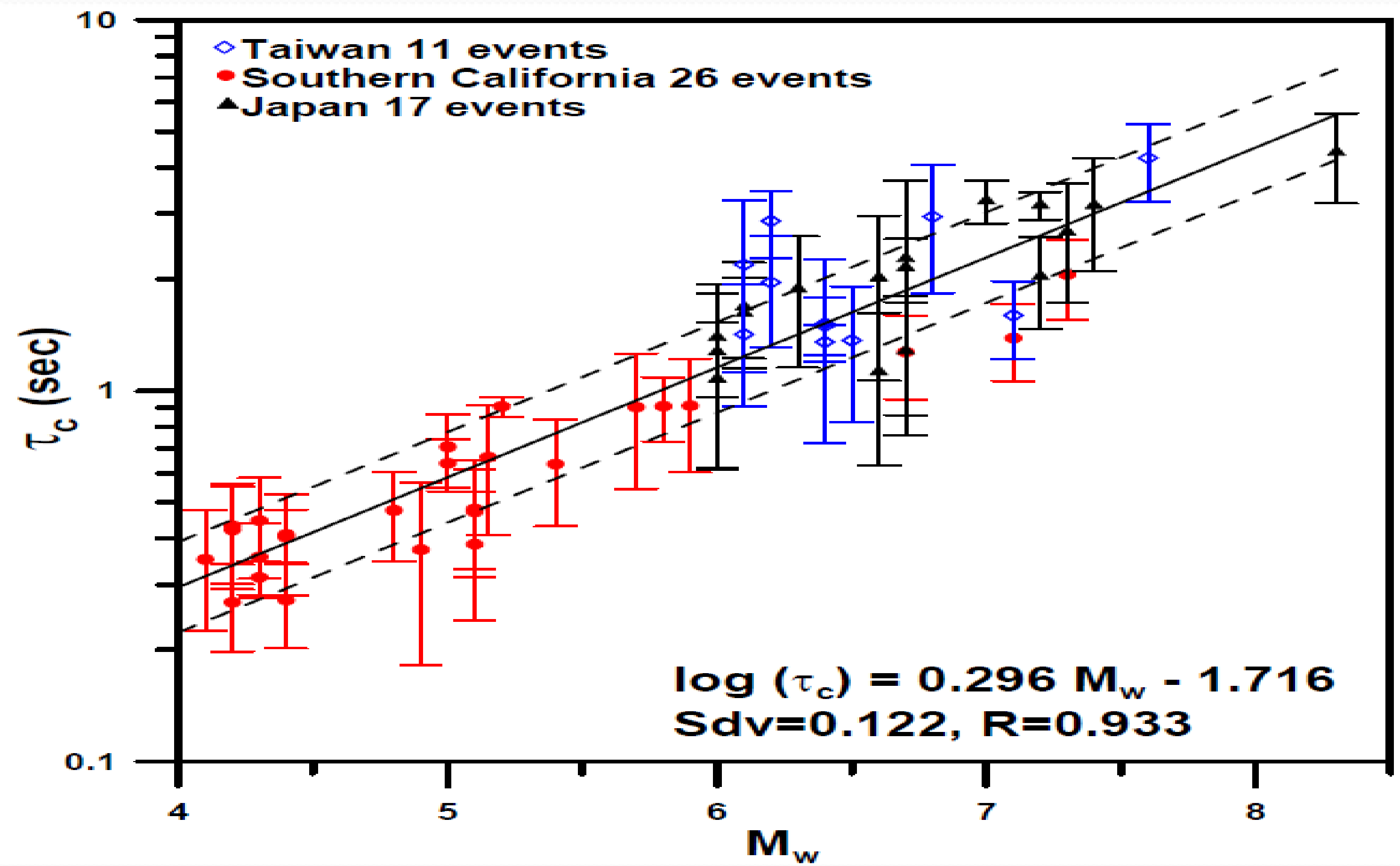
$$\tau_c = \frac{2\pi}{\sqrt{r}}$$

- where,

$$r = \frac{\int_0^{\tau_0} \dot{u}^2(t)\,dt}{\int_0^{\tau_0} u(t)\,dt}$$

- τo = duration of record used (usually 3 sec),
- $\dot{u}(t)$ = velocity and $u(t)$ = displacement obtained from ground motion record on double integration

- When τ_c >1s at a site ,then potential of striking that site is high(Wu & Kanamori 2005a,2005b,2007)



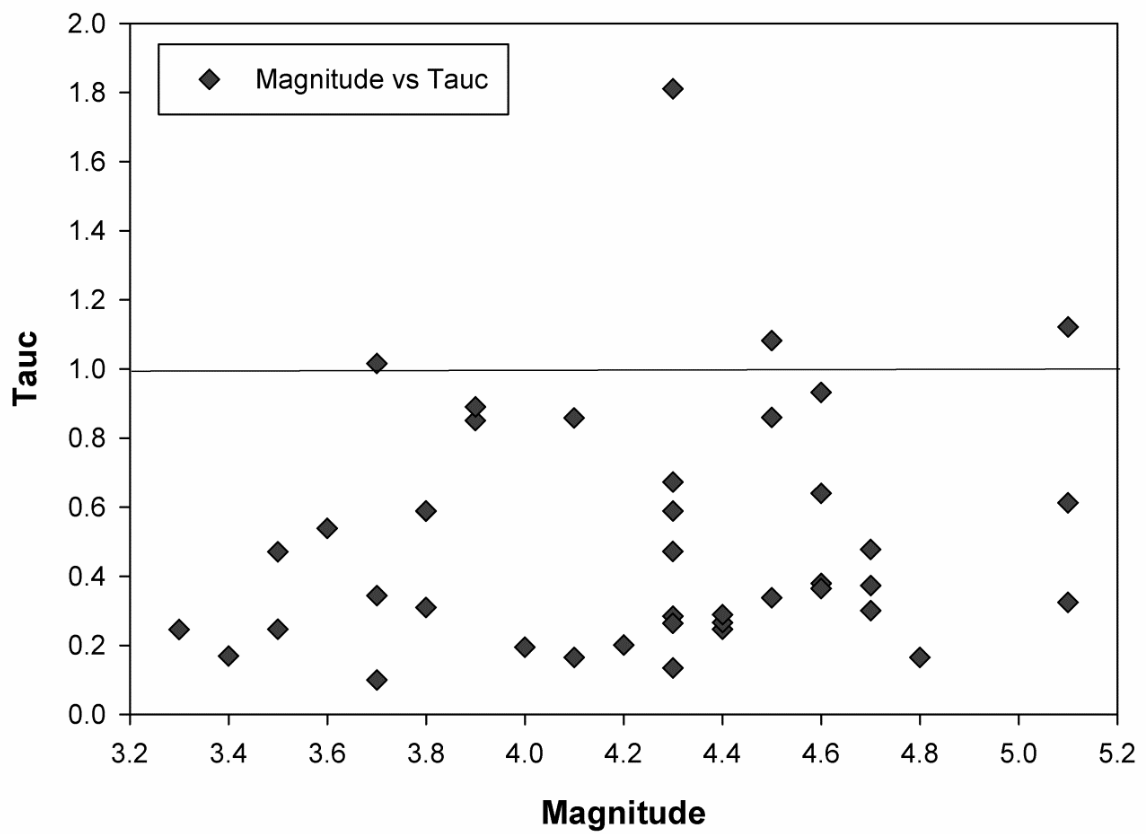
Thus, if a warning is issued at threshold $\tau_c \geq 1$ means a warning is issued for magnitude 6 or above.

Data Used

- Data from 30 seismic stations covering five regions viz., Garhwal Himalaya, Kumaon Himalaya, Northeast Himalaya and National Capital Regions (NCR) used in analysis.
- 41 strong motion records of 30 earthquakes, recorded at 30 seismic stations considered in the analysis.
- The near field records recorded till year 2011 having epicenter distance range up to 60 km, magnitude ranging from 3.3 to 5.1 and focal depth 2 to 33 km have been analyzed in the present study .

- Considered 41 vertical component of Indian strong motion records. These records were integrated to obtain velocity and displacement. A high-pass fifth order Butterworth filter with a cutoff frequency of 0.075 Hz was applied on the record to remove the low frequency drift in velocity and displacement signal. We adopted a time window length of 3 sec starting from the P-wave arrival time in magnitude estimation.

Plot of τ_c with Magnitude



Results

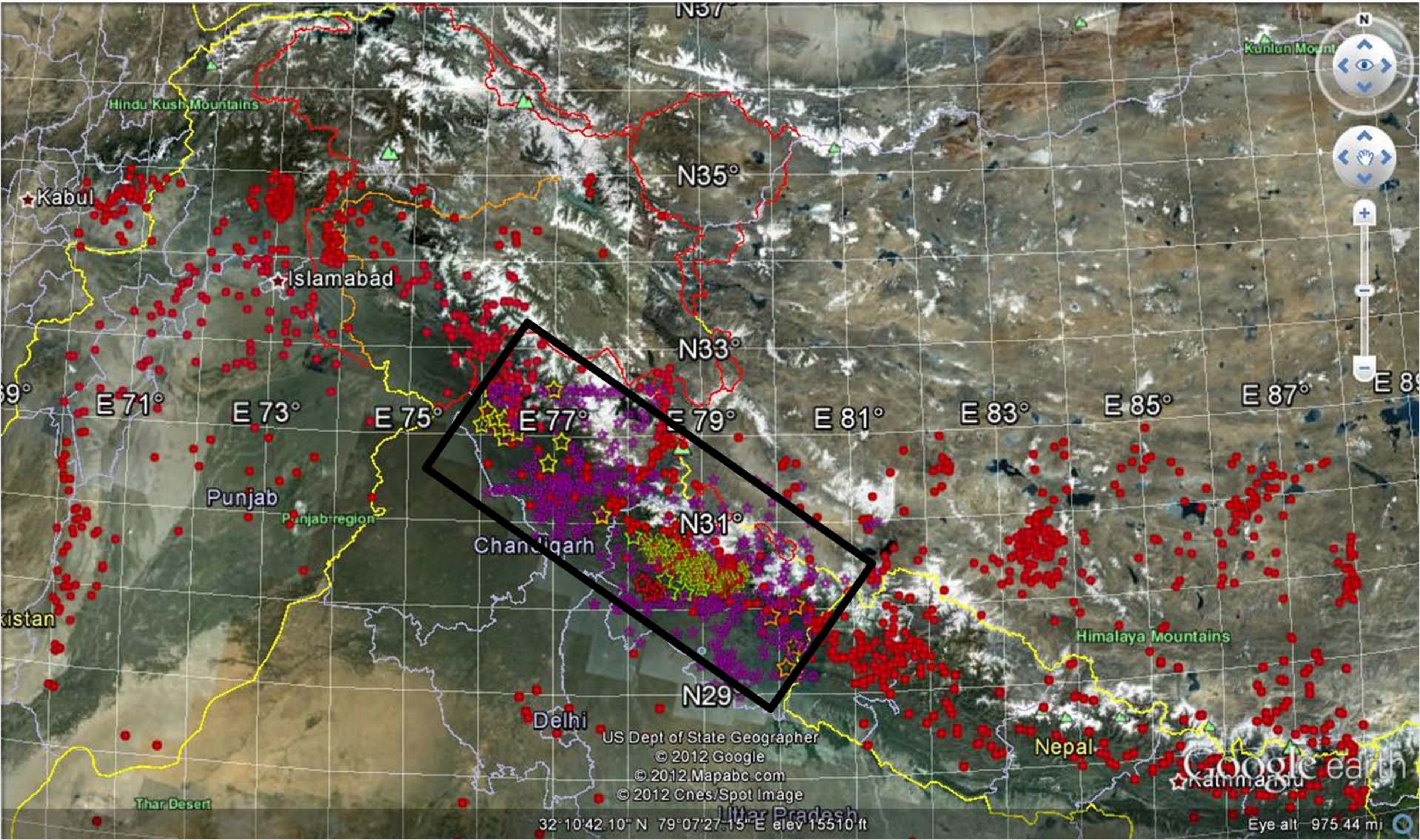
- Figure shows variation of τc values versus magnitude. The distribution of τc values with respect to magnitude show that it is in total agreement in low magnitudes bins ($3 \leq M \leq 4.5$), except two three individual stations.

PreSEIS: Approach application for Earthquake location in Indian region

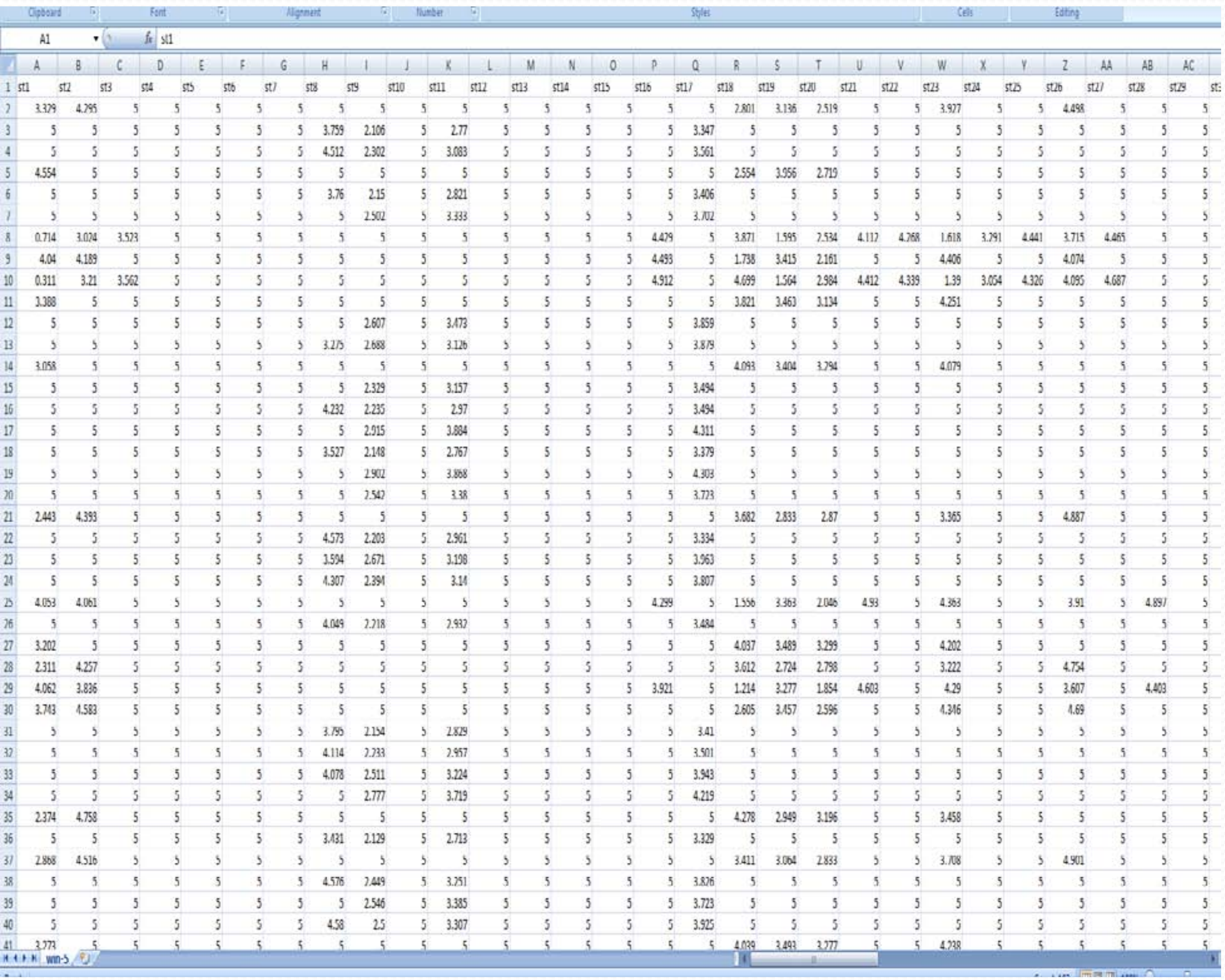
- 1767 earthquake records are considered
- An array of 100 Indian strong ground motion recording instruments
- Velocity model used for locating event in the region

P-wave velocity(Km/sec)	Depth to the top of the layer
3	0
5.2	1
6	15
7.91	46

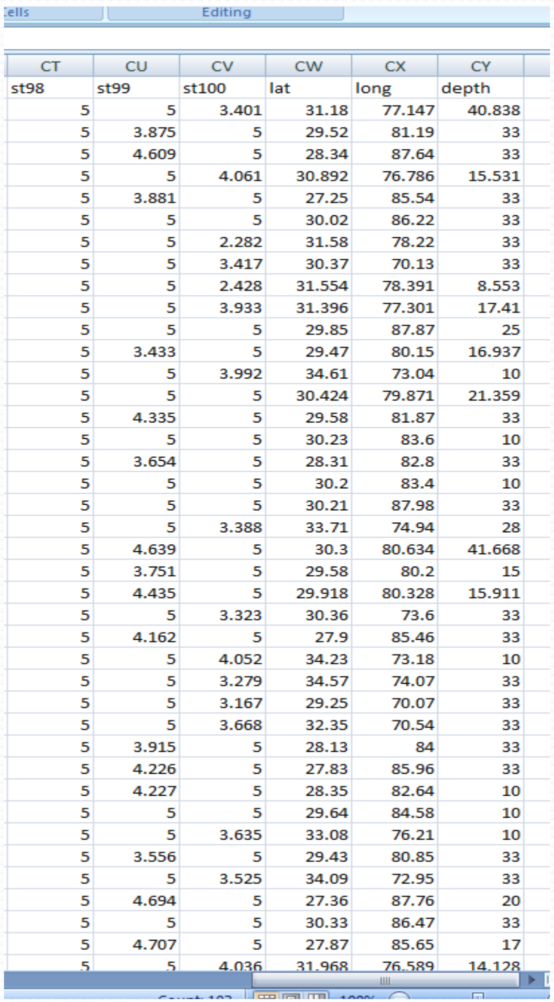
STUDY REGION



Input sheet for a time window of 5 sec

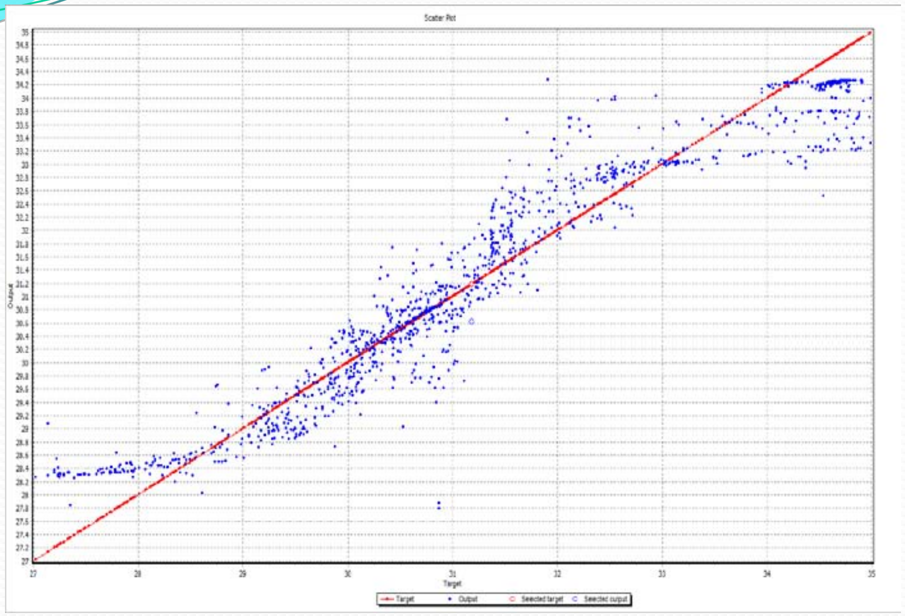


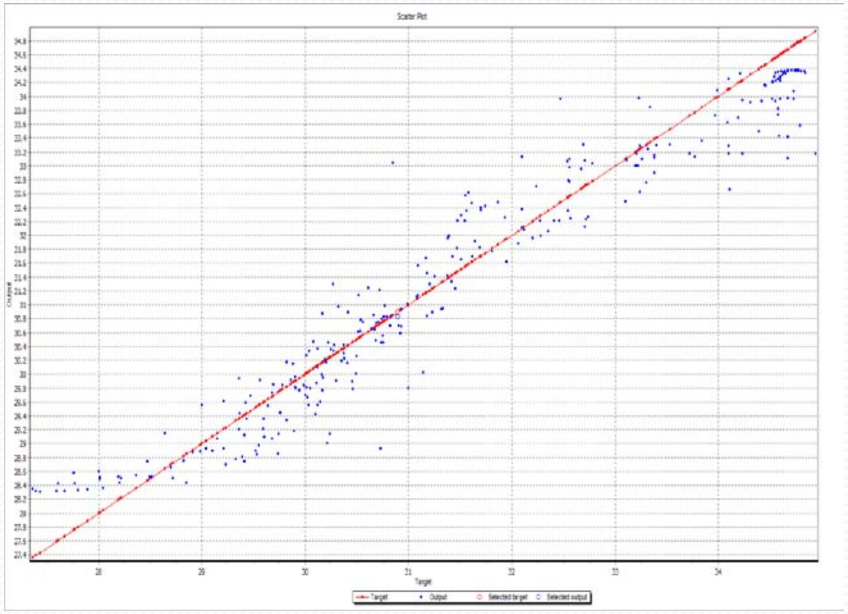
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	AB	AC
1	st1	st2	st3	st4	st5	st6	st7	st8	st9	st10	st11	st12	st13	st14	st15	st16	st17	st18	st19	st20	st21	st22	st23	st24	st25	st26	st27	st28	st29
2	3.329	4.295	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	2.801	3.136	2.519	5	5	3.927	5	5	4.498	5	5	5
3	5	5	5	5	5	5	5	3.759	2.106	5	2.77	5	5	5	5	5	3.347	5	5	5	5	5	5	5	5	5	5	5	5
4	5	5	5	5	5	5	5	4.512	2.302	5	3.083	5	5	5	5	5	3.561	5	5	5	5	5	5	5	5	5	5	5	5
5	4.554	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	2.554	3.956	2.719	5	5	5	5	5	5	5	5	5
6	5	5	5	5	5	5	5	3.76	2.15	5	2.821	5	5	5	5	5	3.406	5	5	5	5	5	5	5	5	5	5	5	5
7	5	5	5	5	5	5	5	5	2.502	5	3.333	5	5	5	5	5	3.702	5	5	5	5	5	5	5	5	5	5	5	5
8	0.714	3.024	3.523	5	5	5	5	5	5	5	5	5	5	5	5	4.429	5	3.871	1.595	2.534	4.117	4.268	1.618	3.291	4.441	3.715	4.465	5	5
9	4.04	4.189	5	5	5	5	5	5	5	5	5	5	5	5	5	4.493	5	1.738	3.415	2.161	5	5	4.406	5	5	4.074	5	5	5
10	0.311	3.21	3.562	5	5	5	5	5	5	5	5	5	5	5	5	4.912	5	4.699	1.564	2.984	4.412	4.339	1.39	3.054	4.326	4.095	4.687	5	5
11	3.388	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	3.821	3.463	3.134	5	5	4.251	5	5	5	5	5	5
12	5	5	5	5	5	5	5	5	2.607	5	3.473	5	5	5	5	5	3.859	5	5	5	5	5	5	5	5	5	5	5	5
13	5	5	5	5	5	5	5	3.275	2.688	5	3.126	5	5	5	5	5	3.879	5	5	5	5	5	5	5	5	5	5	5	5
14	3.058	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	4.093	3.404	3.794	5	5	4.079	5	5	5	5	5	5
15	5	5	5	5	5	5	5	5	2.329	5	3.157	5	5	5	5	5	3.494	5	5	5	5	5	5	5	5	5	5	5	5
16	5	5	5	5	5	5	5	4.232	2.235	5	2.97	5	5	5	5	5	3.494	5	5	5	5	5	5	5	5	5	5	5	5
17	5	5	5	5	5	5	5	5	2.915	5	3.884	5	5	5	5	5	4.311	5	5	5	5	5	5	5	5	5	5	5	5
18	5	5	5	5	5	5	5	3.527	2.148	5	2.767	5	5	5	5	5	3.379	5	5	5	5	5	5	5	5	5	5	5	5
19	5	5	5	5	5	5	5	5	2.902	5	3.868	5	5	5	5	5	4.303	5	5	5	5	5	5	5	5	5	5	5	5
20	5	5	5	5	5	5	5	5	2.542	5	3.38	5	5	5	5	5	3.723	5	5	5	5	5	5	5	5	5	5	5	5
21	2.443	4.393	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	3.682	2.833	2.87	5	5	3.365	5	5	4.887	5	5	5
22	5	5	5	5	5	5	5	4.573	2.203	5	2.961	5	5	5	5	5	3.334	5	5	5	5	5	5	5	5	5	5	5	5
23	5	5	5	5	5	5	5	3.594	2.671	5	3.198	5	5	5	5	5	3.963	5	5	5	5	5	5	5	5	5	5	5	5
24	5	5	5	5	5	5	5	4.307	2.394	5	3.14	5	5	5	5	5	3.807	5	5	5	5	5	5	5	5	5	5	5	5
25	4.053	4.061	5	5	5	5	5	5	5	5	5	5	5	5	5	4.299	5	1.556	3.363	2.046	4.93	5	4.363	5	5	3.91	5	4.897	5
26	5	5	5	5	5	5	5	4.049	2.218	5	2.932	5	5	5	5	5	3.484	5	5	5	5	5	5	5	5	5	5	5	5
27	3.202	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	4.037	3.489	3.299	5	5	4.202	5	5	5	5	5	5
28	2.311	4.257	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	3.612	2.724	2.798	5	5	3.222	5	5	4.754	5	5	5
29	4.062	3.836	5	5	5	5	5	5	5	5	5	5	5	5	5	3.921	5	1.214	3.277	1.854	4.603	5	4.29	5	5	3.607	5	4.403	5
30	3.743	4.583	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	2.605	3.457	2.596	5	5	4.346	5	5	4.69	5	5	5
31	5	5	5	5	5	5	5	3.795	2.154	5	2.829	5	5	5	5	5	3.41	5	5	5	5	5	5	5	5	5	5	5	5
32	5	5	5	5	5	5	5	4.114	2.233	5	2.957	5	5	5	5	5	3.501	5	5	5	5	5	5	5	5	5	5	5	5
33	5	5	5	5	5	5	5	4.078	2.511	5	3.224	5	5	5	5	5	3.943	5	5	5	5	5	5	5	5	5	5	5	5
34	5	5	5	5	5	5	5	5	2.777	5	3.719	5	5	5	5	5	4.219	5	5	5	5	5	5	5	5	5	5	5	5
35	2.374	4.758	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	4.278	2.949	3.196	5	5	3.458	5	5	5	5	5	5
36	5	5	5	5	5	5	5	3.431	2.129	5	2.713	5	5	5	5	5	3.329	5	5	5	5	5	5	5	5	5	5	5	5
37	2.868	4.516	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	3.411	3.064	2.833	5	5	3.708	5	5	4.901	5	5	5
38	5	5	5	5	5	5	5	4.576	2.449	5	3.251	5	5	5	5	5	3.826	5	5	5	5	5	5	5	5	5	5	5	5
39	5	5	5	5	5	5	5	5	2.546	5	3.385	5	5	5	5	5	3.723	5	5	5	5	5	5	5	5	5	5	5	5
40	5	5	5	5	5	5	5	4.58	2.5	5	3.307	5	5	5	5	5	3.925	5	5	5	5	5	5	5	5	5	5	5	5
41	3.273	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	4.039	3.493	3.277	5	5	4.238	5	5	5	5	5	5

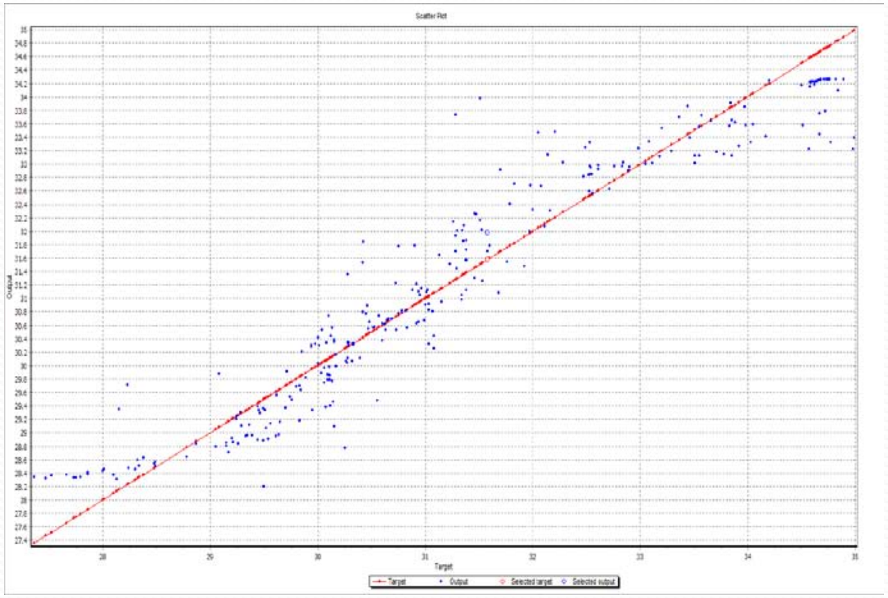


CT	CU	CV	CW	CX	CY
st98	st99	st100	lat	long	depth
5	5	3.401	31.18	77.147	40.838
5	3.875	5	29.52	81.19	33
5	4.609	5	28.34	87.64	33
5	5	4.061	30.892	76.786	15.531
5	3.881	5	27.25	85.54	33
5	5	5	30.02	86.22	33
5	5	2.282	31.58	78.22	33
5	5	3.417	30.37	70.13	33
5	5	2.428	31.554	78.391	8.553
5	5	3.933	31.396	77.301	17.41
5	5	5	29.85	87.87	25
5	3.433	5	29.47	80.15	16.937
5	5	3.992	34.61	73.04	10
5	5	5	30.424	79.871	21.359
5	4.335	5	29.58	81.87	33
5	5	5	30.23	83.6	10
5	3.654	5	28.31	82.8	33
5	5	5	30.2	83.4	10
5	5	5	30.21	87.98	33
5	5	3.388	33.71	74.94	28
5	4.639	5	30.3	80.634	41.668
5	3.751	5	29.58	80.2	15
5	4.435	5	29.918	80.328	15.911
5	5	3.323	30.36	73.6	33
5	4.162	5	27.9	85.46	33
5	5	4.052	34.23	73.18	10
5	5	3.279	34.57	74.07	33
5	5	3.167	29.25	70.07	33
5	5	3.668	32.35	70.54	33
5	3.915	5	28.13	84	33
5	4.226	5	27.83	85.96	33
5	4.227	5	28.35	82.64	10
5	5	5	29.64	84.58	10
5	5	3.635	33.08	76.21	10
5	3.556	5	29.43	80.85	33
5	5	3.525	34.09	72.95	33
5	4.694	5	27.36	87.76	20
5	5	5	30.33	86.47	33
5	4.707	5	27.87	85.65	17
5	5	4.036	31.968	76.589	14.128

5 sec window latitude training, testing and Validation







5 sec window latitude, longitude and depth results

Training

Latitude

Summary

	Target	Output	AE	ARE
Mean:	31.329717	31.305168	0.404345	0.012852
Std Dev:	1.990847	1.849809	0.368114	0.011622
Min:	27.02	27.790994	0.000106	0.000003
Max:	34.99	34.27444	3.079006	0.099741

Correlation: 0.962187
R-squared: 0.912618

Longitude

Summary

	Target	Output	AE	ARE
Mean:	31.322021	31.311208	0.41781	0.013314
Std Dev:	1.974788	1.87542	0.374902	0.011908
Min:	27.36	28.197322	0.000411	0.000013
Max:	34.99	34.26524	2.460906	0.078362

Correlation: 0.958806
R-squared: 0.910407

Depth

Summary

	Target	Output	AE	ARE
Mean:	31.425911	31.395539	0.430253	0.013621
Std Dev:	2.050147	1.868344	0.342004	0.010726
Min:	27.36	28.256508	0.004134	0.000134
Max:	34.94	34.265076	1.666265	0.054196

Correlation: 0.965002
R-squared: 0.91346

Testing

Latitude

Summary

	Target	Output	AE	ARE
Mean:	78.641499	78.649643	0.92039	0.011703
Std Dev:	4.680268	4.376379	0.851663	0.010957
Min:	70	72.075744	0.000465	0.000006
Max:	88	85.834145	6.501126	0.083262

Correlation: 0.963871
R-squared: 0.917899

Longitude

Summary

	Target	Output	AE	ARE
Mean:	78.694011	78.668943	0.863964	0.010946
Std Dev:	4.745057	4.422318	0.792111	0.010034
Min:	70.03	71.773664	0.002475	0.000034
Max:	87.95	85.795141	4.3914	0.055743

Correlation: 0.969761
R-squared: 0.92975

Depth

Summary

	Target	Output	AE	ARE
Mean:	78.278121	78.41103	1.026246	0.013146
Std Dev:	4.807759	4.440089	0.952841	0.012362
Min:	70.01	72.168682	0.002437	0.000032
Max:	87.99	85.794832	7.017294	0.089449

Correlation: 0.957646
R-squared: 0.900525

Validation

Latitude

Summary

	Target	Output	AE	ARE
Mean:	25.118957	25.095422	1.620277	0.080666
Std Dev:	11.21568	10.679257	1.773773	0.100283
Min:	8	8.187366	0.000117	0.000004
Max:	45	44.372514	13.444577	0.970916

Correlation: 0.97711
R-squared: 0.949393

Longitude

Summary

	Target	Output	AE	ARE
Mean:	25.196816	25.39301	1.830921	0.094332
Std Dev:	11.036888	10.906807	2.354488	0.16978
Min:	8.014	8.453642	0.008137	0.000687
Max:	44	43.326072	15.552205	1.940629

Correlation: 0.96328
R-squared: 0.925219

Depth

Summary

	Target	Output	AE	ARE
Mean:	25.118957	25.095422	1.620277	0.080666
Std Dev:	11.21568	10.679257	1.773773	0.100283
Min:	8	8.187366	0.000117	0.000004
Max:	45	44.372514	13.444577	0.970916

Correlation: 0.97711
R-squared: 0.949393

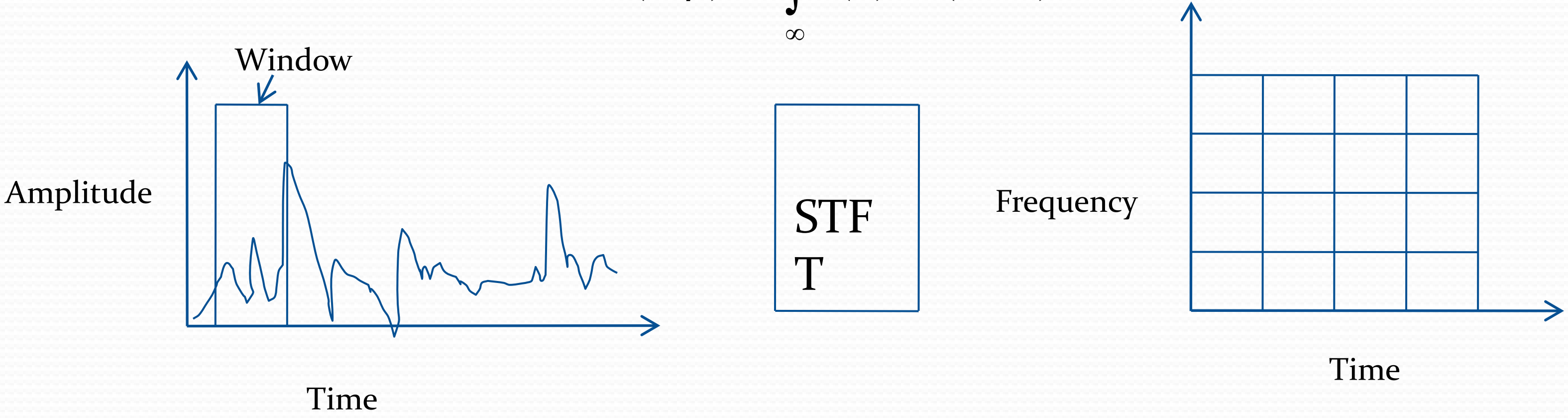
Time frequency distributions (TFDs)

- Short time Fourier transform (STFT)
- Gabor transform (GT)
- Wigner Ville distribution (WVD)
- Gabor Wigner transform (GWT)

- And many more.............

Short time Fourier transform (STFT)

$$STFT(t,f) = \int_{\infty}^{-\infty} x(\tau) w^{*}(t-\tau) e^{-j2\pi f\tau} d\tau$$



•STFT analyses the signal with the help of movable window (i.e. rectangular, Hanning, Hamming etc.)

▪Frequency resolution can be achieved only at the expense poorer time resolution due to the limitations given by uncertainty principle.

Gabor Transform(GT)

$$G(t,f) = \int x(\tau) e^{\frac{-(\tau-t)^2}{2}} e^{-j2\pi f\tau} d\tau$$

- It uses Gaussian window.

- The time-frequency uncertainty is defined as,

$$\Delta t \times \Delta f \geq {}^{1}/_{4\pi}$$

- Similar to the STFT, GT also suffers from time frequency resolution problem because it also depends on window.

Wigner Ville distribution (WVD)

WVD is Fourier transform of the input signal's autocorrelation function.

$$WVD_z(t,f) = \int_{-\infty}^{\infty} z\left(t+\frac{\tau}{2}\right) z^*\left(t-\frac{\tau}{2}\right) e^{-j2\pi f\tau} d\tau$$

where z(t) is the analytic signal of x(t).

- If WVD method compare with GT and STFT, it does not require window to analyze the data.

- This method increases the time frequency resolution to a large extent

- But the major drawback of WVD is cross term interference or unwanted signal

Gabor Wiger Transform (GWT)

- A novel method using time frequency analysis along with Gabor Wiger Transform (GWT) for early warning system is proposed, where earthquake size is estimated by predominant frequency of the initial P wave of velocity data of earthquake signal.
- The predominant frequency is determined by applying the time frequency method on the velocity data of earthquake signal. Which not only provide the information about frequency of initial P-wave but also provides time, where frequency indicates whether it is a larger event or small and time indicates at what time one needs to take the decision to issue the warning.

GABOR WIGNER TRANSFORM (GWT)

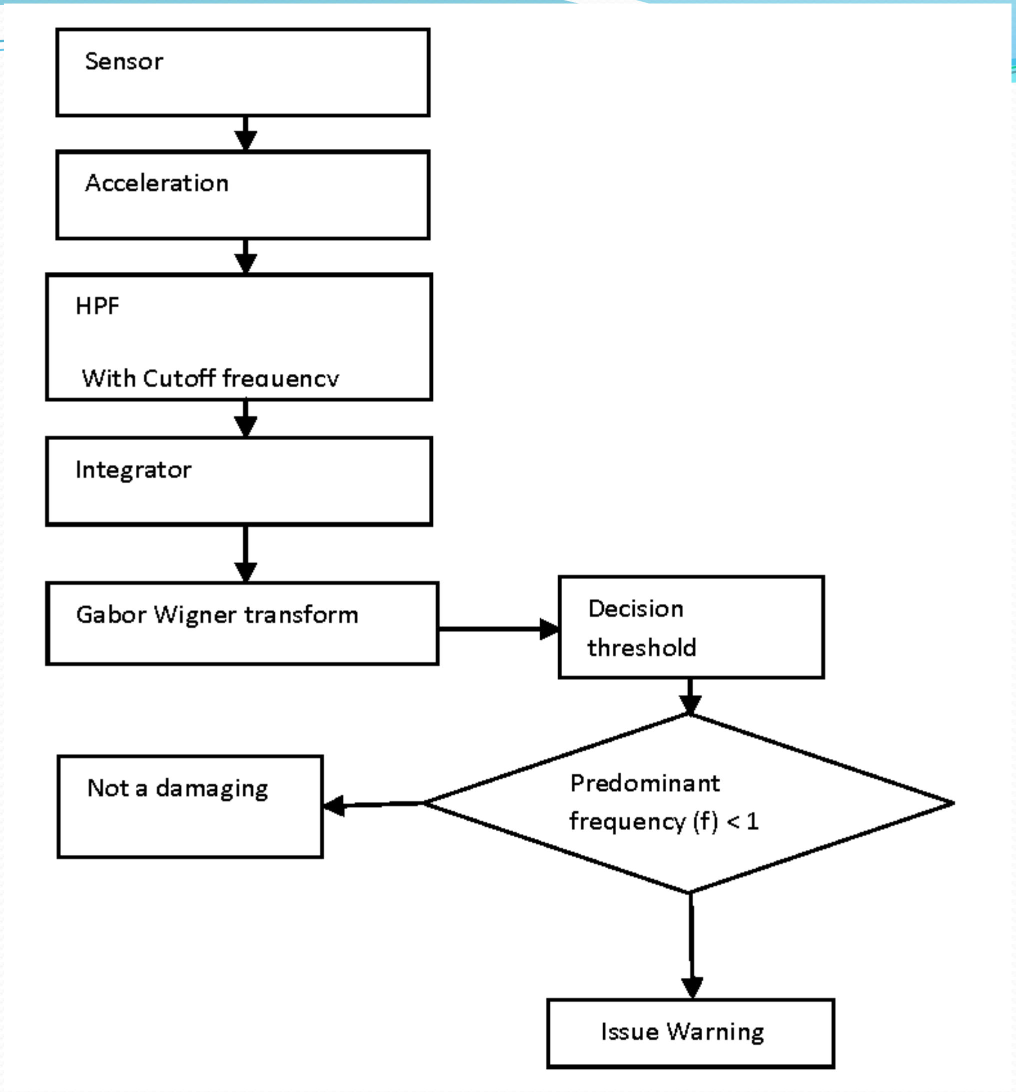
GWT is defined by the following mathematical expressions.

$$GWT_z(t, f) = GT_z(t, f)WVD_z(t, f)$$

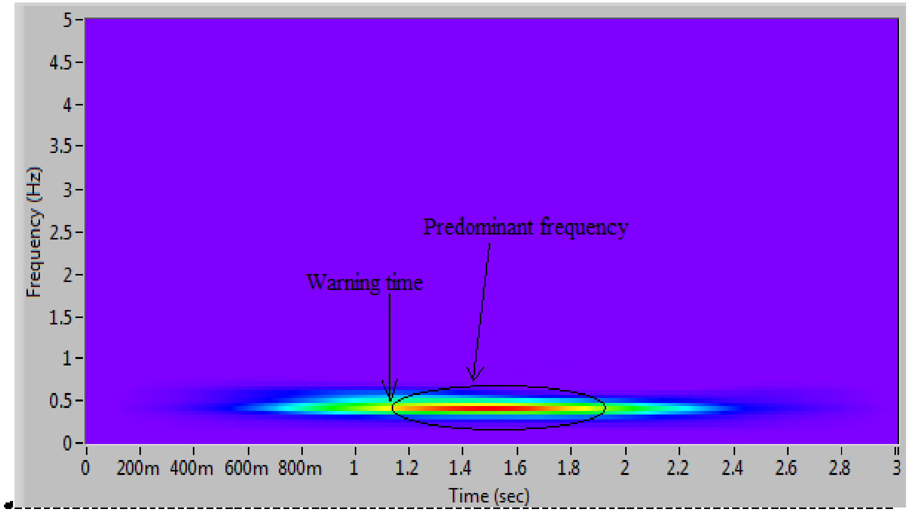
•GWT is a combination of two time frequency planes i.e. GT and WVD

•GWT takes the linked advantages of both transform: outstanding time frequency resolution in WVD and lack of cross term interference in GT.

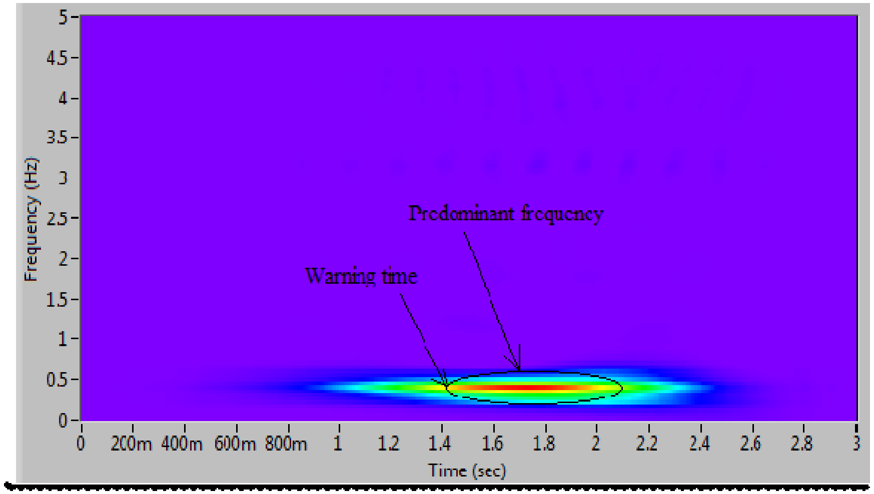
•GWT provides the best result in comparison to the STFT, GT and WVD.



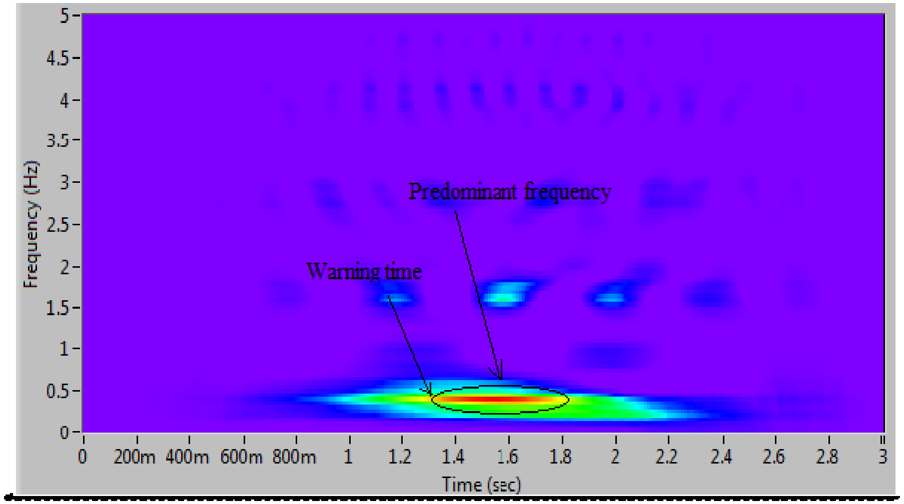
Flow chart showing various steps involved in processing



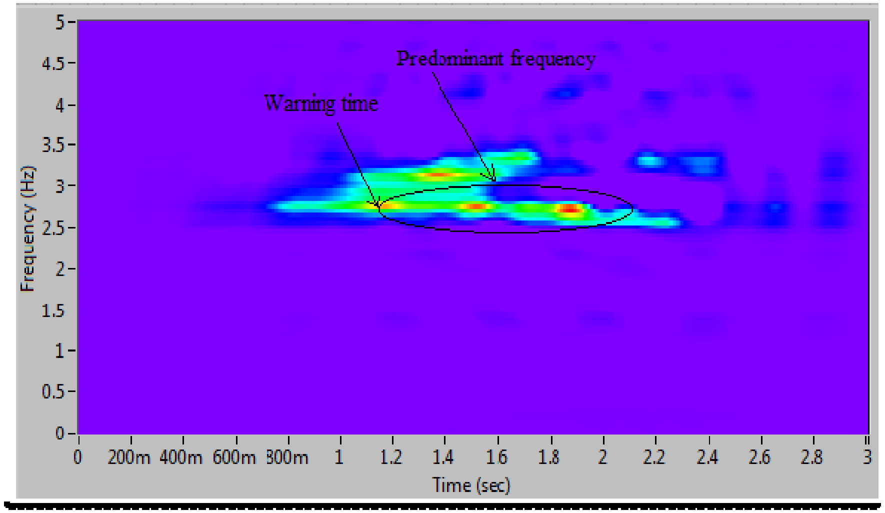
(a). Time frequency analysis of velocity signal up to 3sec with Mag. 7.1 at an epicentral distance 32km



(b). Time frequency analysis of velocity signal up to 3sec with Mag. 7.1 at an epicentral distance 34km

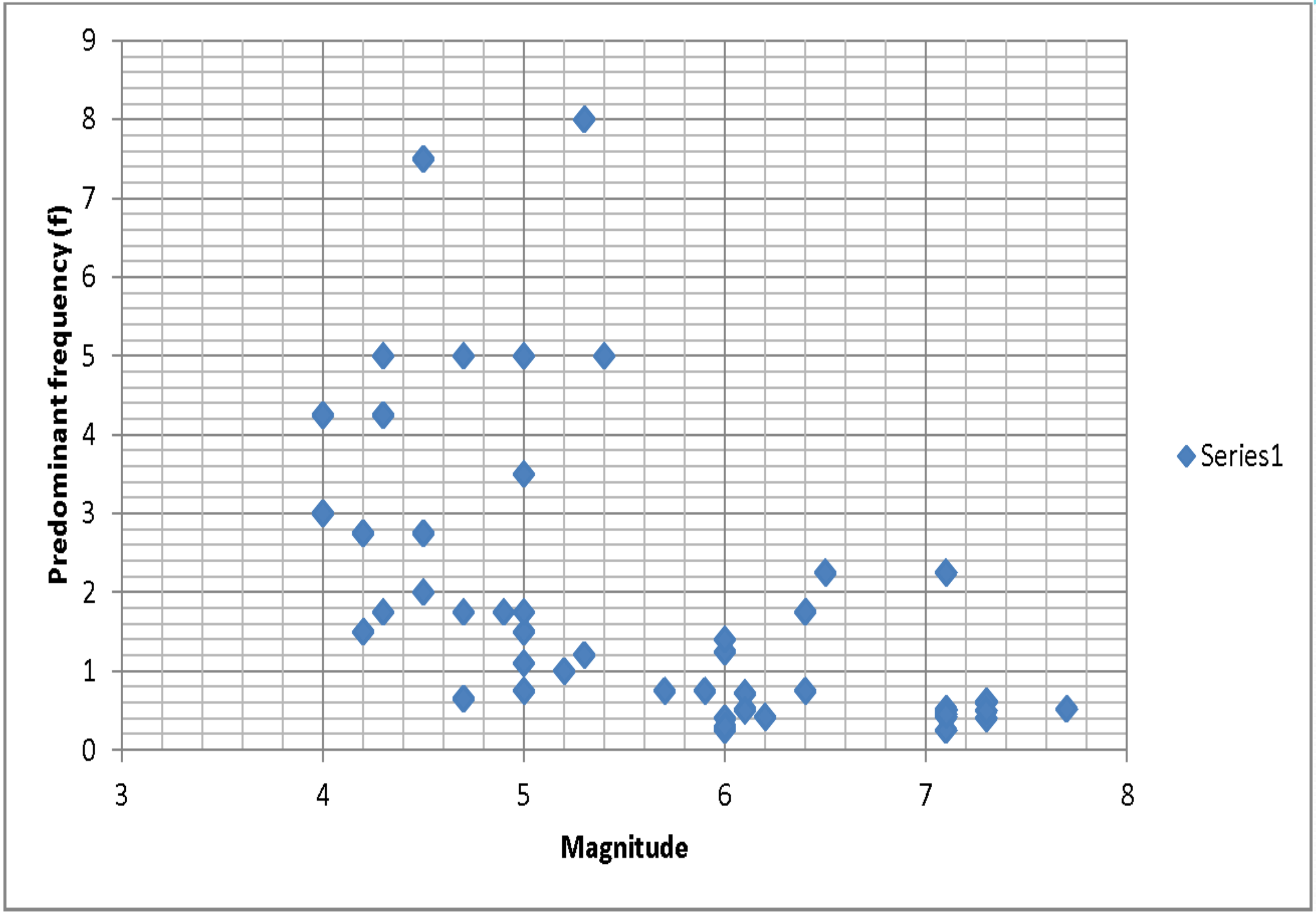


(c). Time frequency analysis of velocity signal up to 3sec with Mag. 7.3 at an epicentral distance 37km



(d). Time frequency analysis of velocity signal up 3sec with Mag. 4.5 at an epicentral distance 51km

- This analysis was carried out for 50 time histories from 20 earthquakes from K-NET with magnitude ranging from 4.2 to 7.7. Figure shows the plot of Magnitude with predominant frequency based on above data. From figure, it is clear that distribution of predominant frequency are in agreement with results obtained from other studies.



Predominant frequency (f)
0
1
2
3
4
5
6
7
8
9
3
4
5
6
7
8
Magnitude
Series1

CONCLUSIONS

- Our most potential EQ source is Himalayas and most vulnerable places are at 100 to 300 Kms
- Thus EEW seems very promising for us and our country can get benefits of EEW which no other country can get.
- Entire technology is available and only requires a strong initiative to put the system

Thank you