International Conference on
Tenets for Geosystem Surety (TGS-2026)

Theme Lecture

Seismic site characterization: Improvising consistently

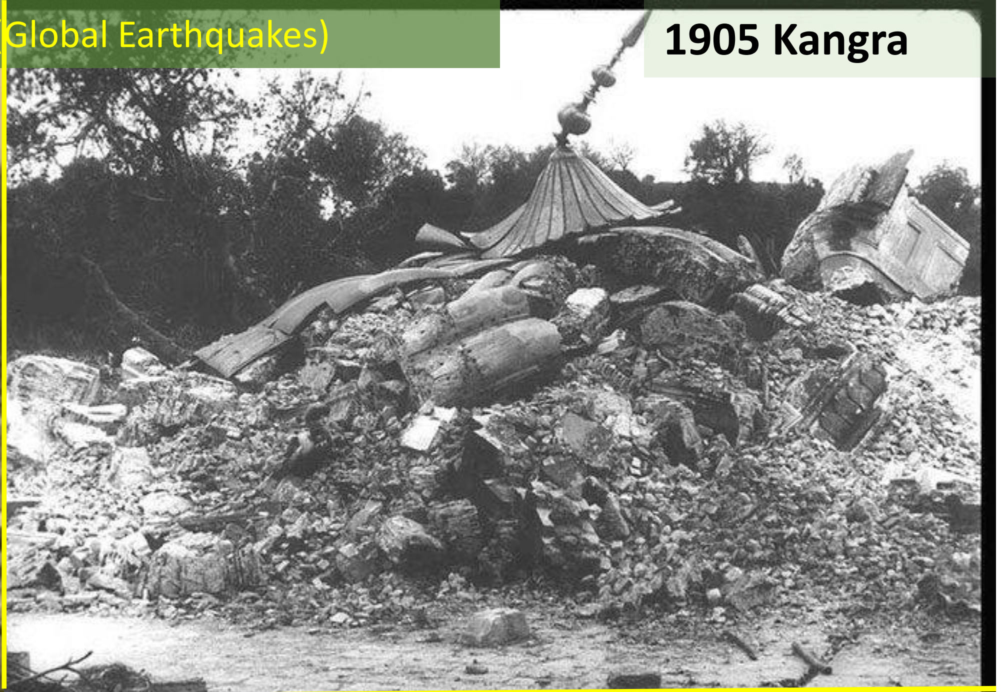
Dr. Abhishek Kumar, Associate Professor, IIT Guwahati

&

Dr. Naveen James, Associate Professor, IIT Ropar


1897 Shillong

Source: Encyclopedia (Global Earthquakes)


1905 Kangra


1934 Bihar-Nepal

Source: Bihar State Disaster Management Authority

2005 Kashmir

Microzonation is defined as the zonation with respect to ground motion characteristics taking into account source and site conditions (ISSMGE/TC4, 1999).

- **Helpful** in **mitigation** and **rehabilitation** works during and after an earthquake.
- Also for city **planning, vulnerability studies** and for **risk assessment** etc.

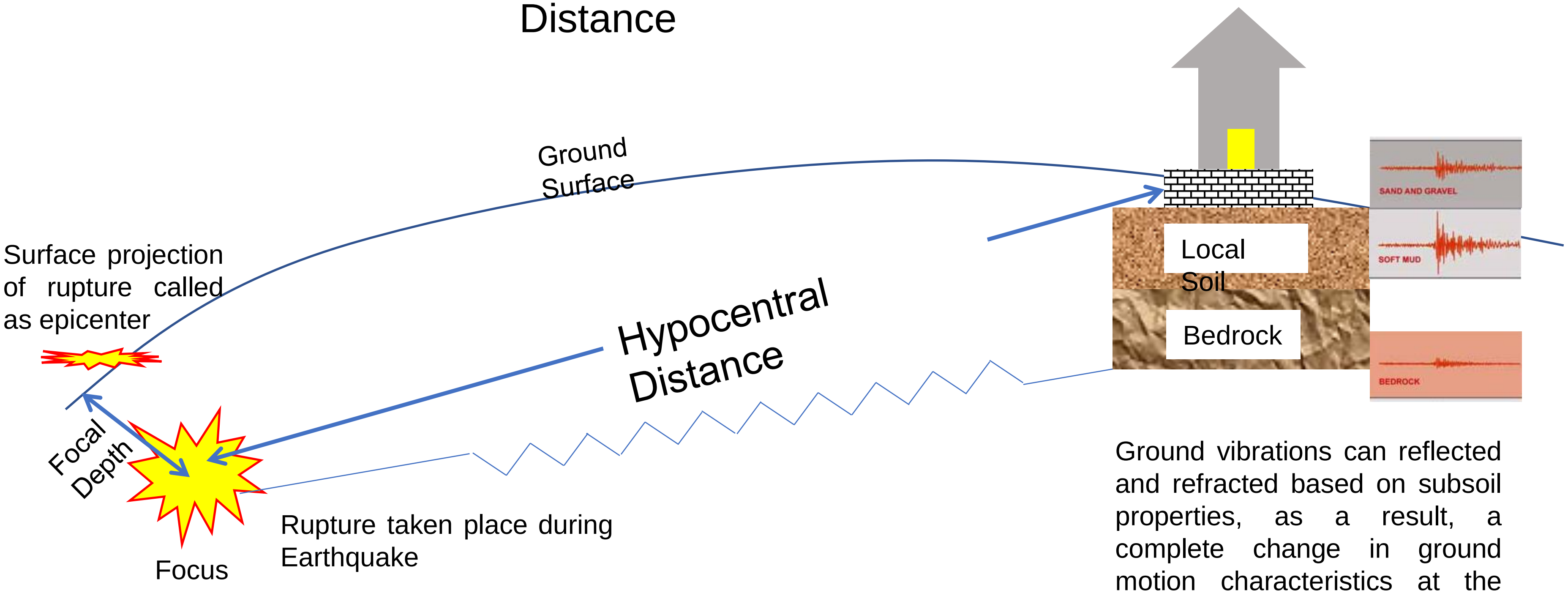
Introduction to local site effect

Ground motion at a site

Source Characteristics (epicentral coordinates, focal depth, strike, dip, rupture length, rupture width, target event magnitude and focal mechanism, directivity effect etc.

Path Characteristics Strength properties, frequency content modification, attenuation characteristics of ground motion

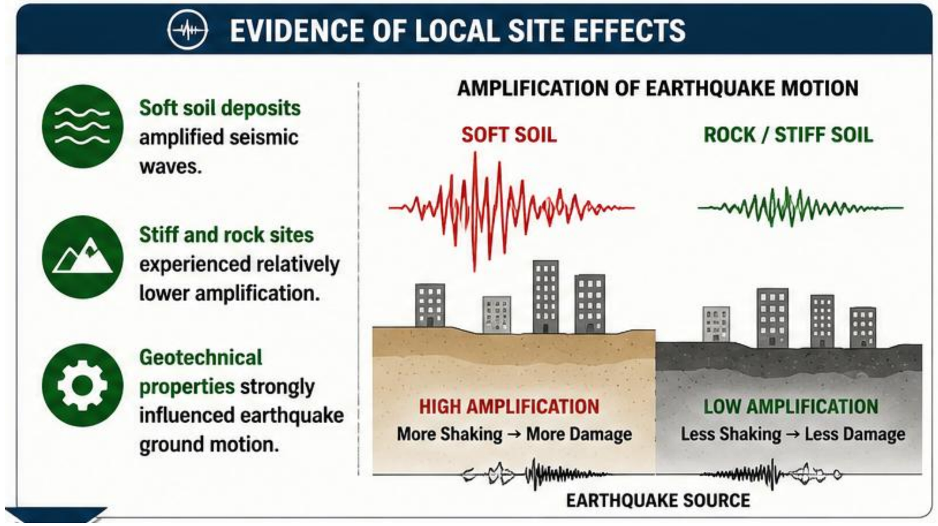
Site Characteristics Rock/ soil condition, coordinates of the site, range of frequency of interest, amplification between bedrock and engineering rock

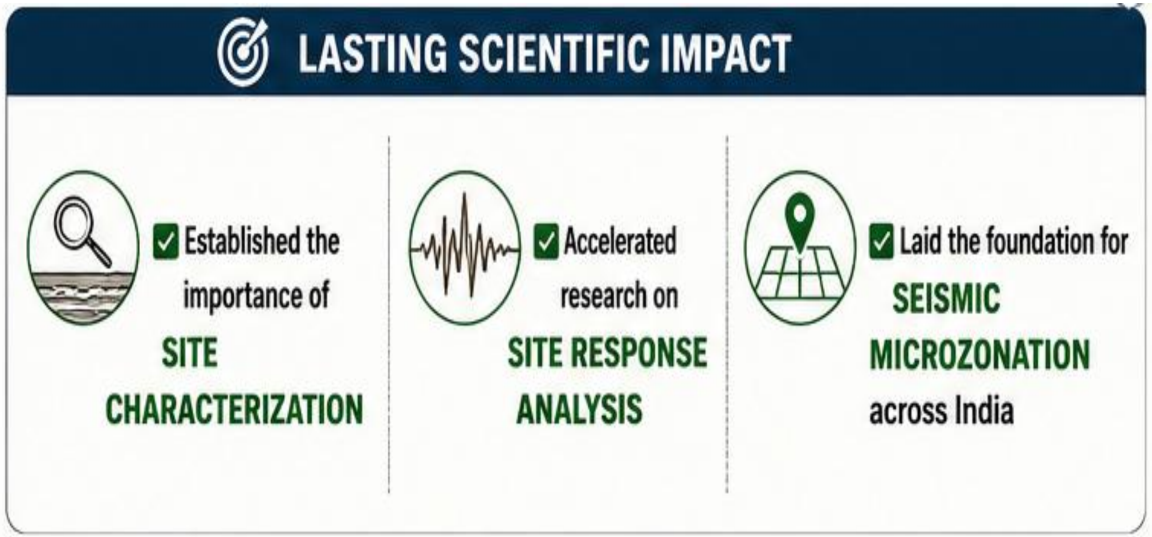


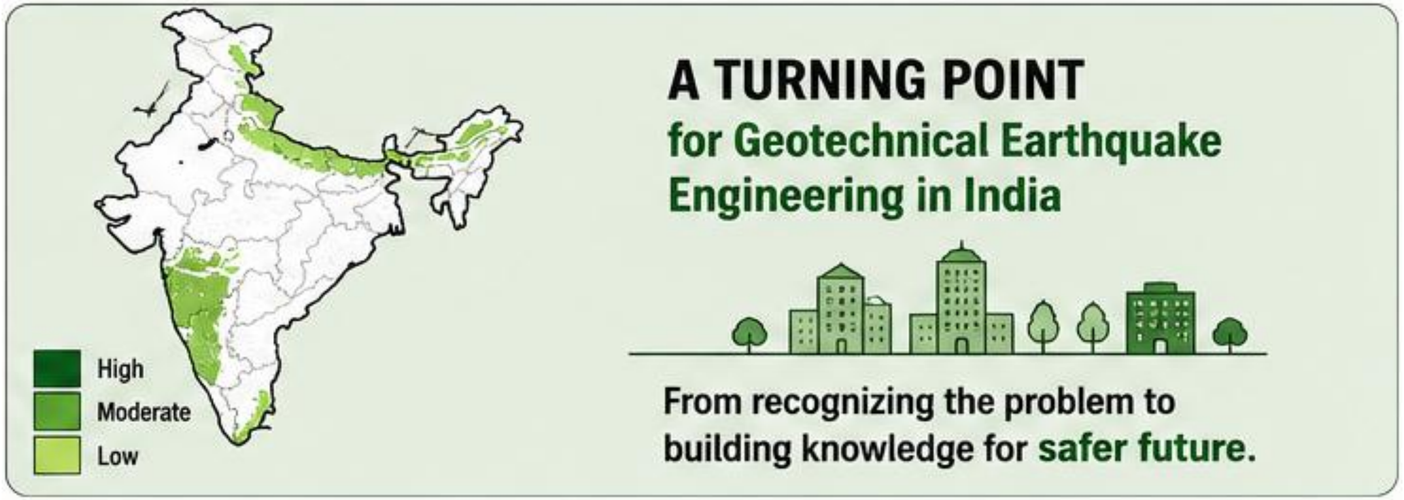
Ground vibrations can reflected and refracted based on subsoil properties, as a result, a complete change in ground motion characteristics at the surface compared to bedrock

Local site effect In Indian Scenario

2001 Bhuj Earthquake







Works Led by Prof. T.G Sitharam

Prof. P Anbazhagan	Site characterization and site response studies for Bangalore urban center
Dr. Abhishek Kumar Sharma	Site characterization and site response studies for Lucknow and indo-Gangetic plane
Dr. Naveen James	Site characterization and site response studies for Critical Installation site – Nuclear Power Plant site
Dr. Arjun Sil	Site characterization and site response studies for Northeast India

Works Led by Prof. T.G Sitharam

Key Milestones

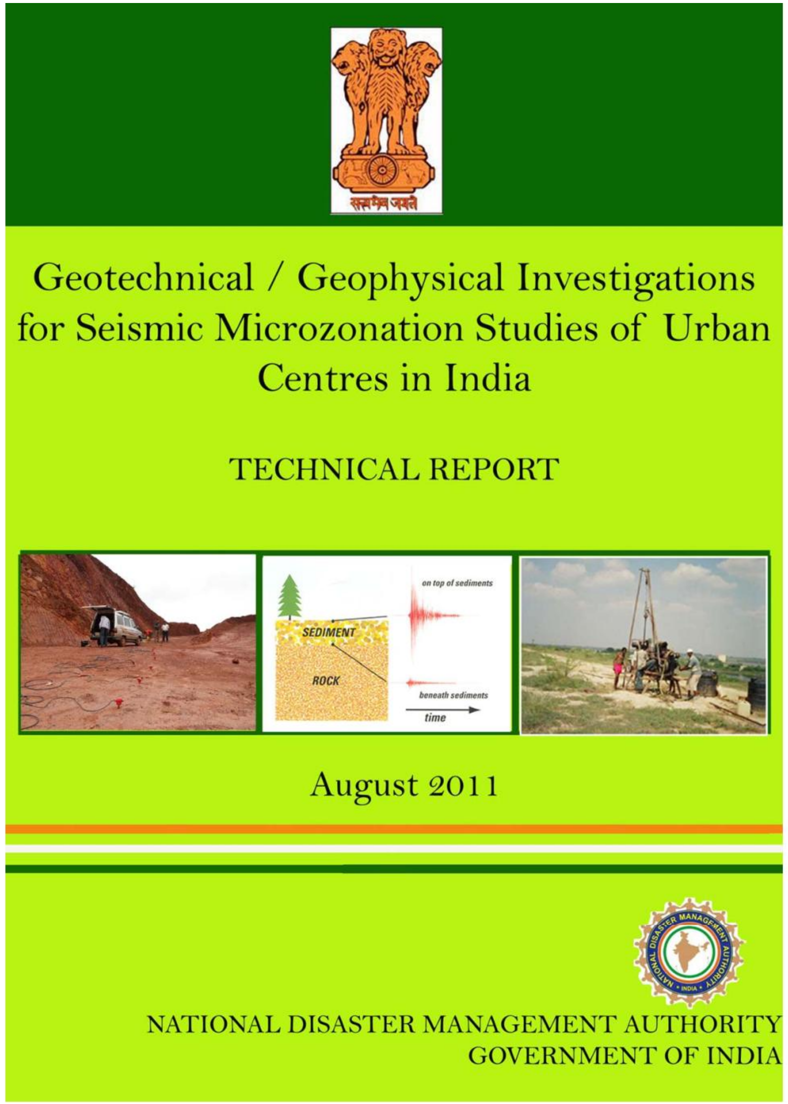
Performing geophysical site characterization using MASW technique

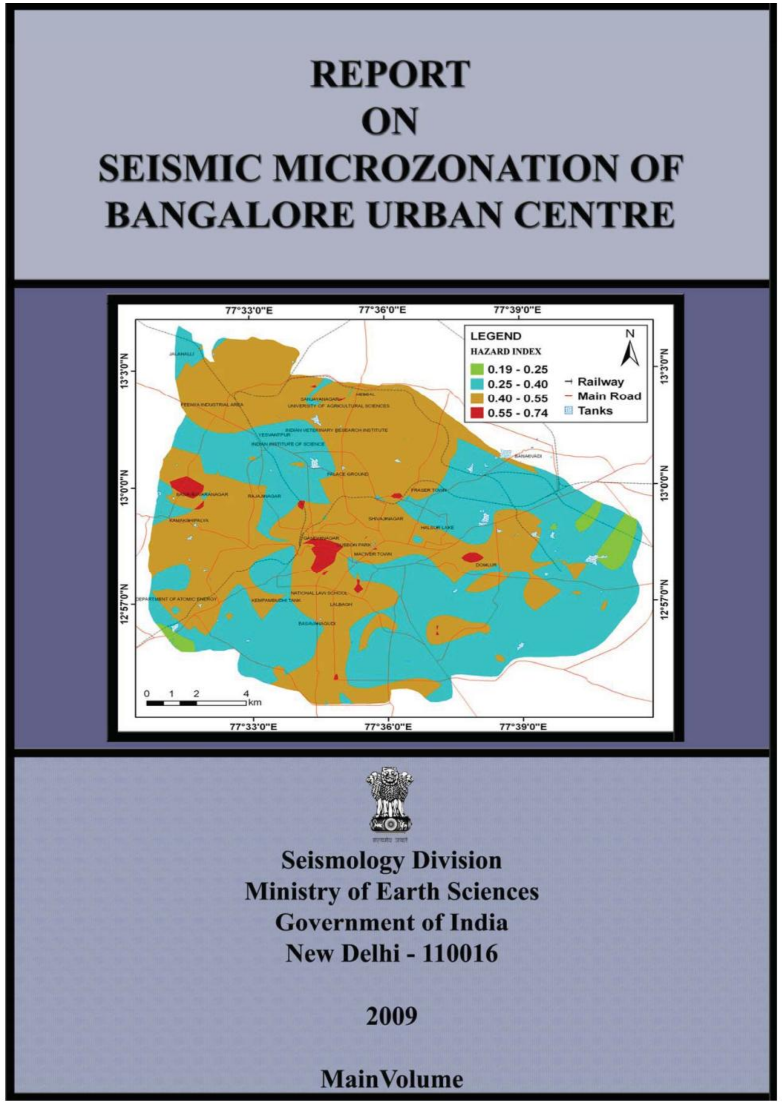
Applying Energy corrections in SPT for seismic site characterization

Developing correlation between SPT-N values and Vs for various regions

Carrying out ground response analysis for seismic microzonation

Works Led by Prof. T.G Sitharam





“Site Characterization/ Classification”

Methods

There are three methods to perform site characterization

- Geological and Geomorphologic methods
- Geotechnical Methods
- Geophysical methods

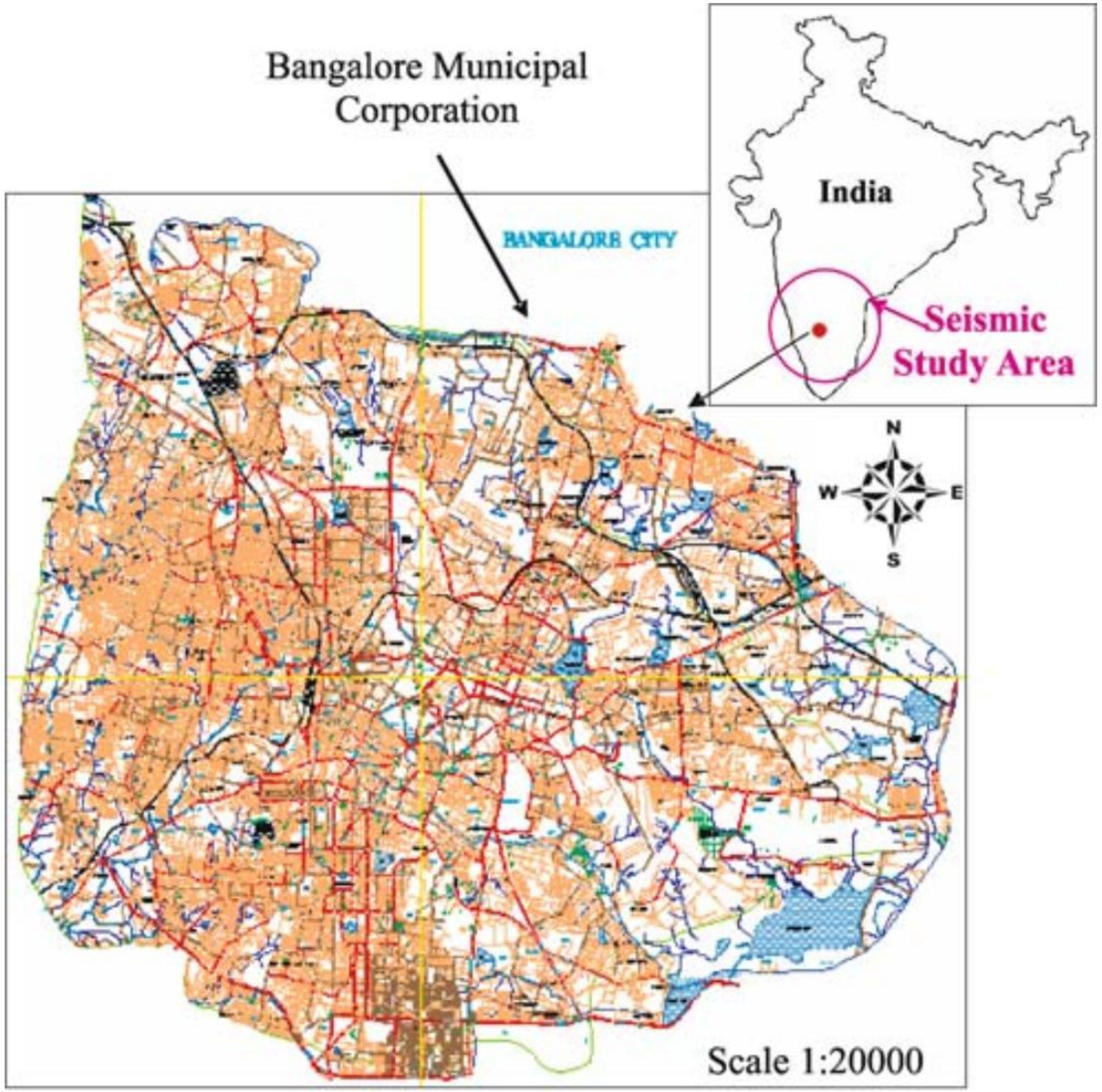
- A site characterization for seismic microzonation using geological, geo-technical, and geophysical data
- Geotechnical tests include standard penetration tests (SPT), dilatometer tests (DMT), pressure meter tests, and seismic cone penetration tests (SCPT), of which SPT is the most widely used in many countries because of the availability of existing data.
- Spectral Analysis of Surface Waves (SASW) and Multi-channel Analysis of Surface Waves (MASW).

Guidelines for Field testing

- **LEVEL I:** For areas comes under low seismicity (regions within seismic zone II) with low population
  - For Homogenous sub-surface – 2 km x 2 km to 5 km x 5 km
  - For heterogeneous sub-surface – 0.5 km x 0.5 km to 2 km x 2 km
- **LEVEL II:** For area comes under moderate to higher seismic hazards with population exceeding 1,00,000;
  - For Homogenous sub-surface – 1 km x 1 km to 3 km x 3 km
  - For heterogeneous sub-surface – 0.5 km x 0.5 km to 1 km x 1 km
- **LEVEL III:** For seismic microzonation of highly vulnerable areas with very high population density (Seismic Zones III, IV and V)
  - For Homogenous sub-surface – 0.5 km x 0.5 km to 2 km x 2 km
  - For heterogeneous sub-surface – 0.1 km x 0.1 km to 0.5 km x 0.5 km

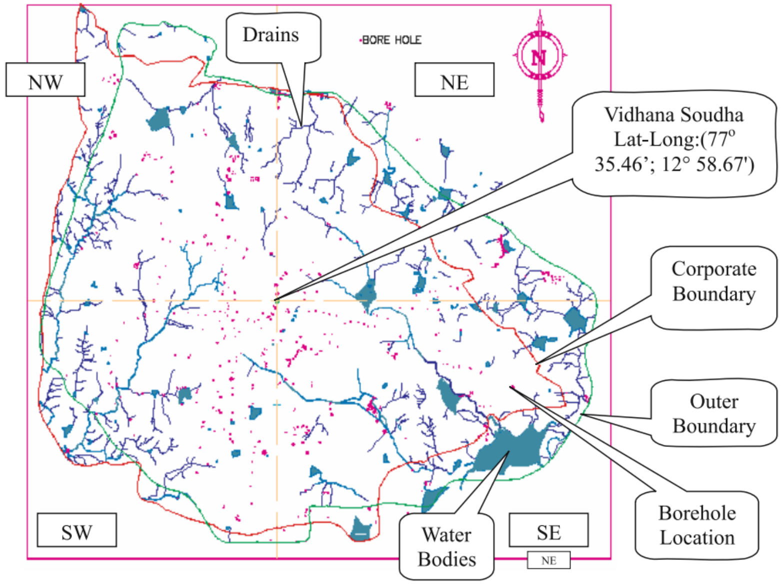
NDMA (2011)

Studies for Bangalore Urban Center

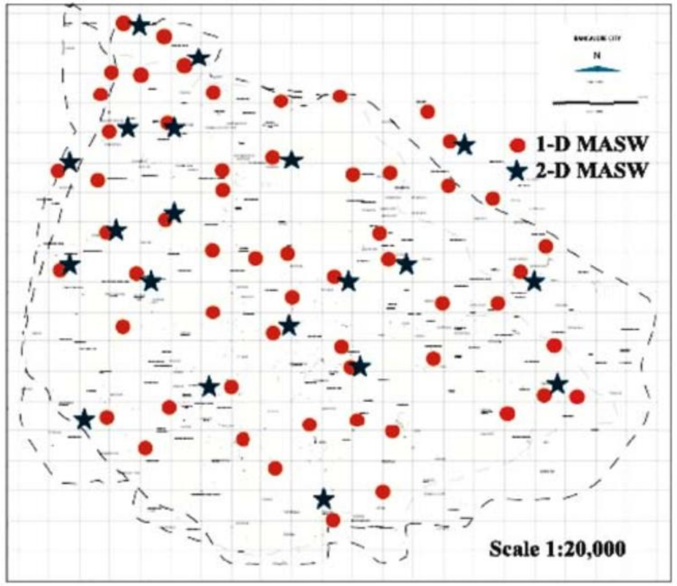


Anbazhagan, P., & Sitharam, T. G. (2008). Seismic microzonation of Bangalore, India. *Journal of Earth System Science*, *117*(Suppl 2), 833-852.

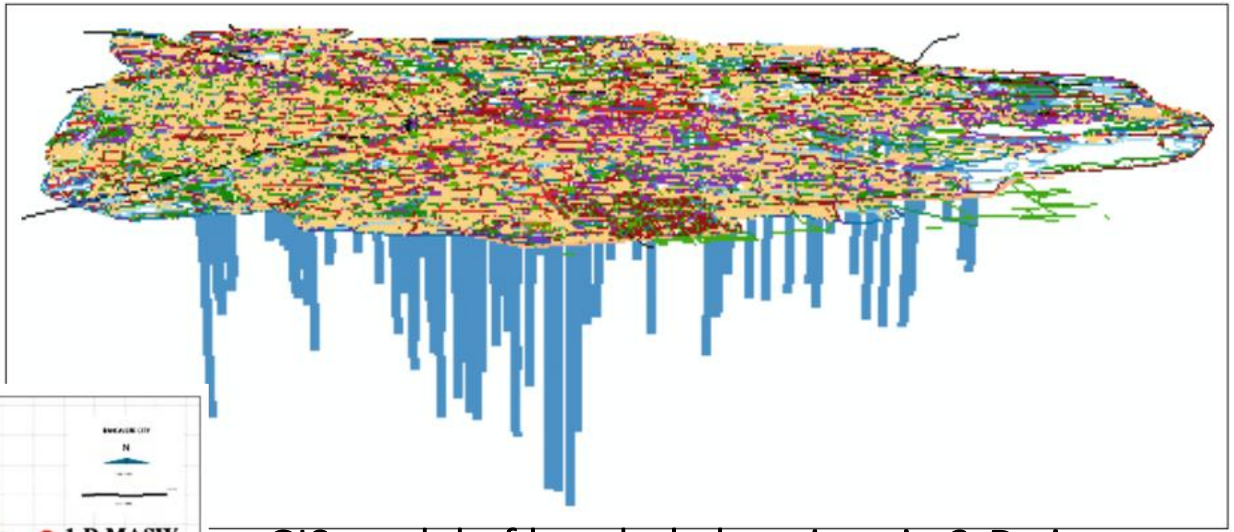
Studies for Bangalore Urban Center



GIS model of borehole locations along with water body features.



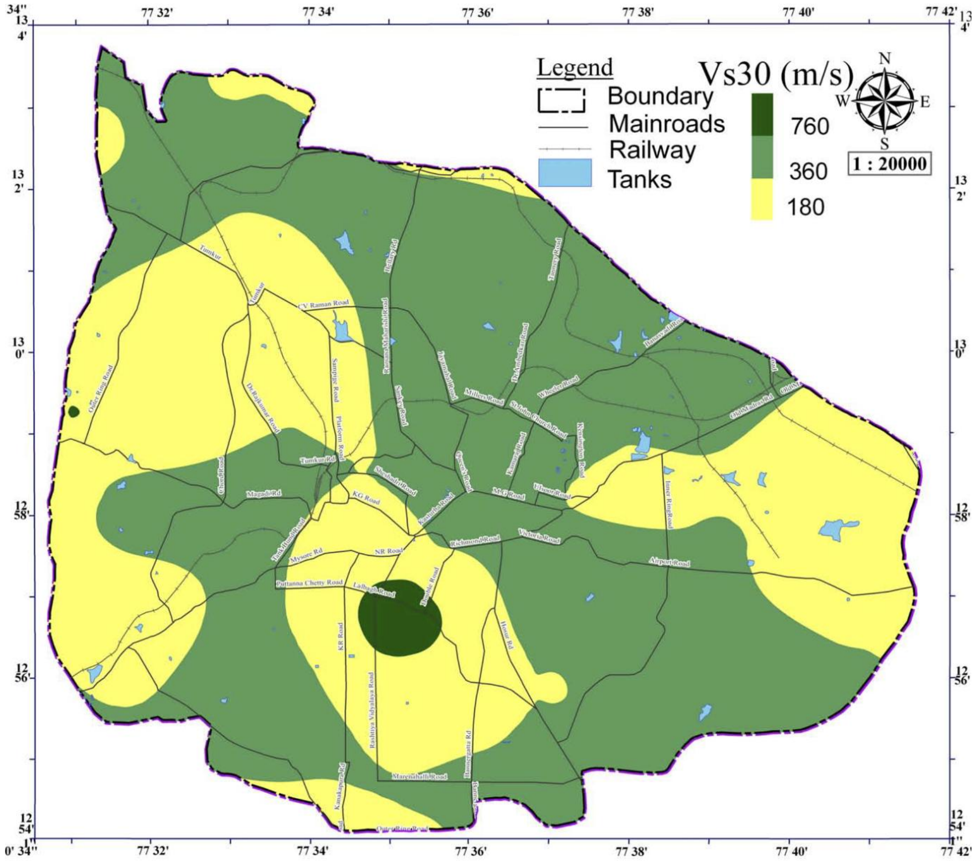
MASW testing locations in Bangalore.



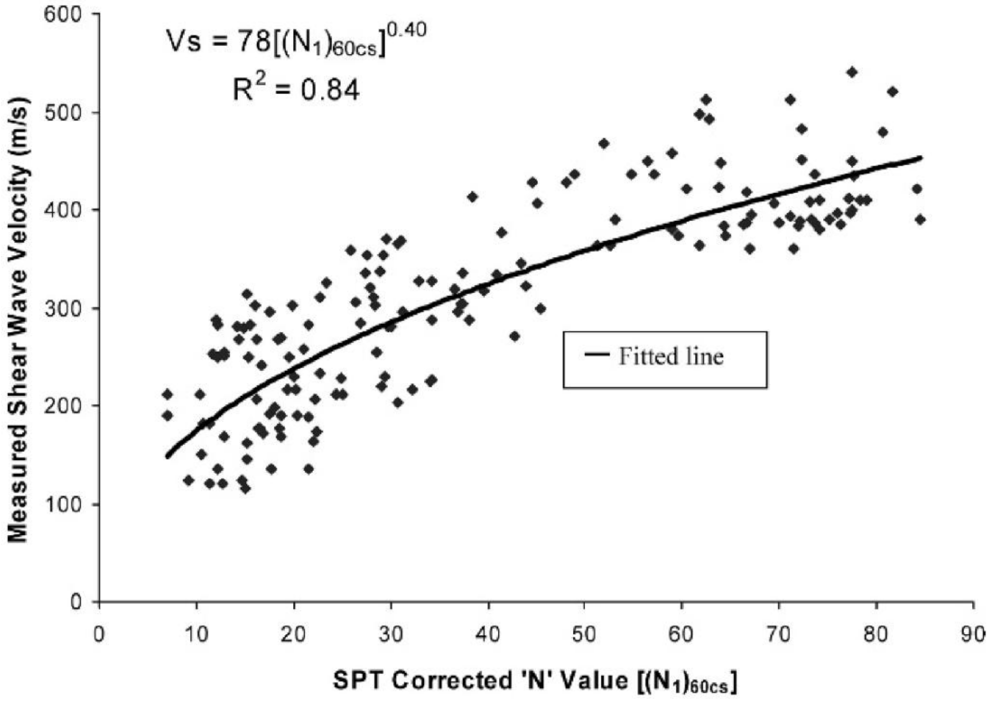
GIS model of borehole locations in 3-D view.

Anbazhagan, P., & Sitharam, T. G. (2008). Mapping of average shear wave velocity for Bangalore region: a case study. *Journal of Environmental and Engineering Geophysics*, *13*(2), 69-84.

Studies for Bangalore Urban Center



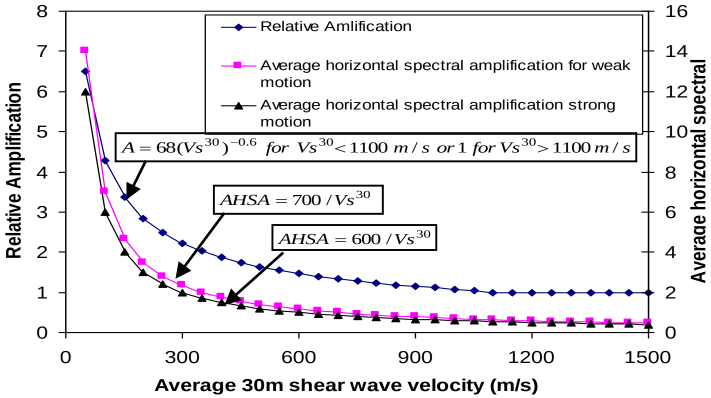
Equivalent shear wave velocity for 30 m depth.

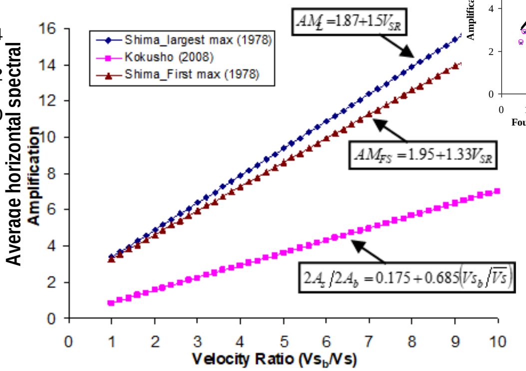


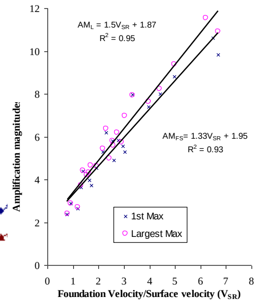
Shear wave velocity versus corrected SPT N values

Seismic Site Classification

$$N_{30} or Vs^{30} = \frac{30 = \sum_{i=1}^{n} d_i}{\sum_{i=1}^{n}\left(\frac{d_i}{N_i \rightleftarrows or Vs_i}\right)}$$

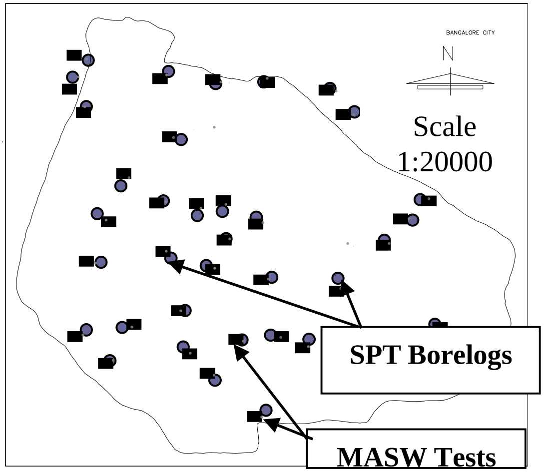


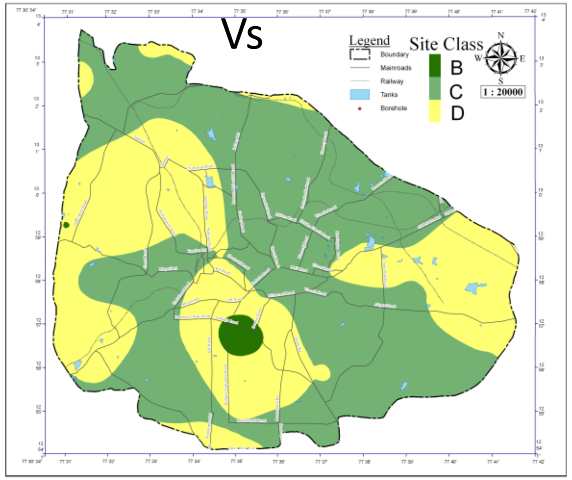


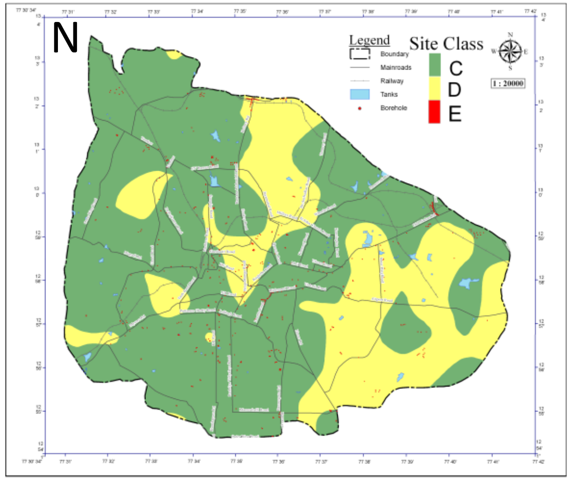


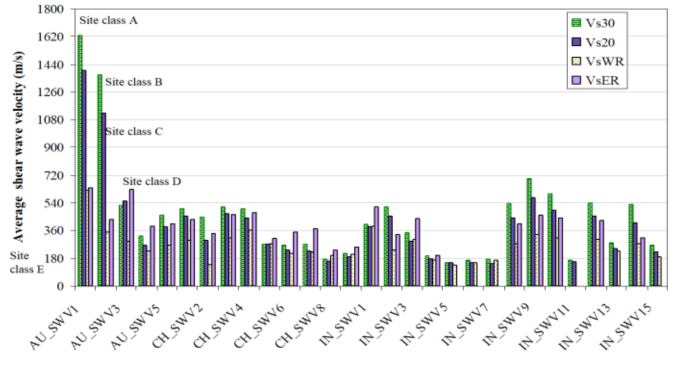
d_i and V_{si}/N_i denote the thickness (in meters) and corresponding shear wave velocity/standard penetration resistance (not to exceed 100 blows/0.3 m as directly measured in the field without corrections) of the i^{th} formation or layer, respectively, in a total of n layers in the top 30 m.

- ❖ SPT N values are directly or conversed as Vs using JRA correlation was used
- ❖ Vs values are measured predominantly using MASW and no validation



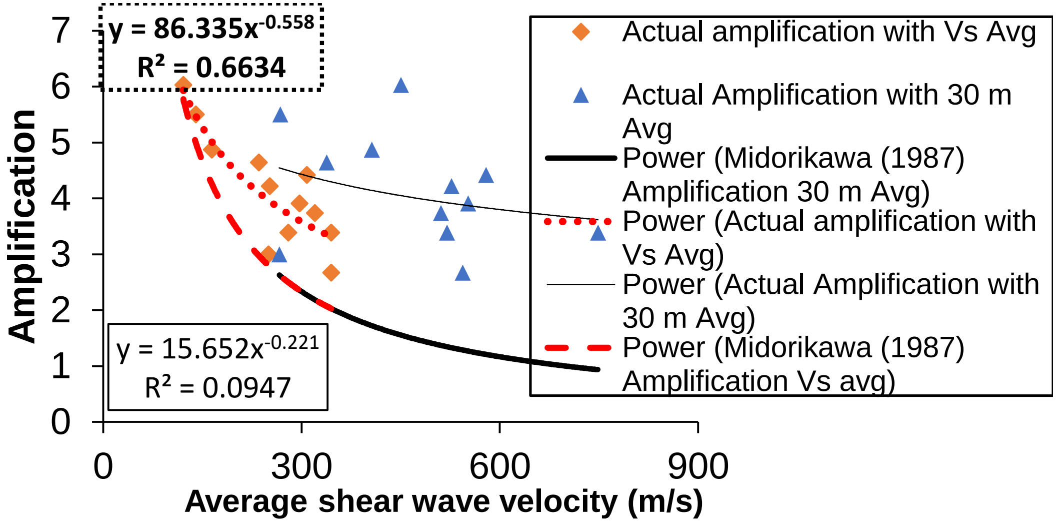


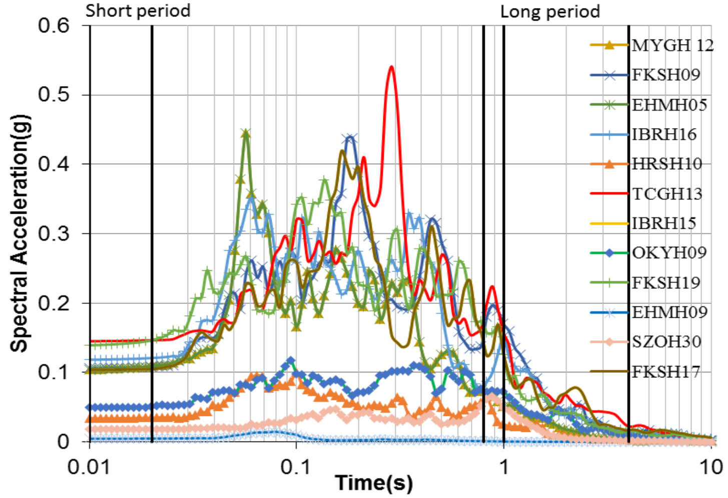


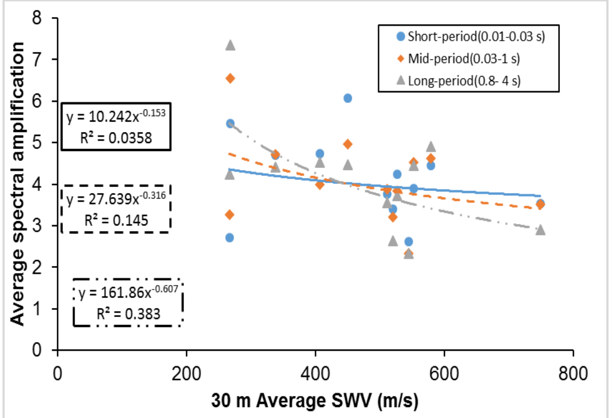


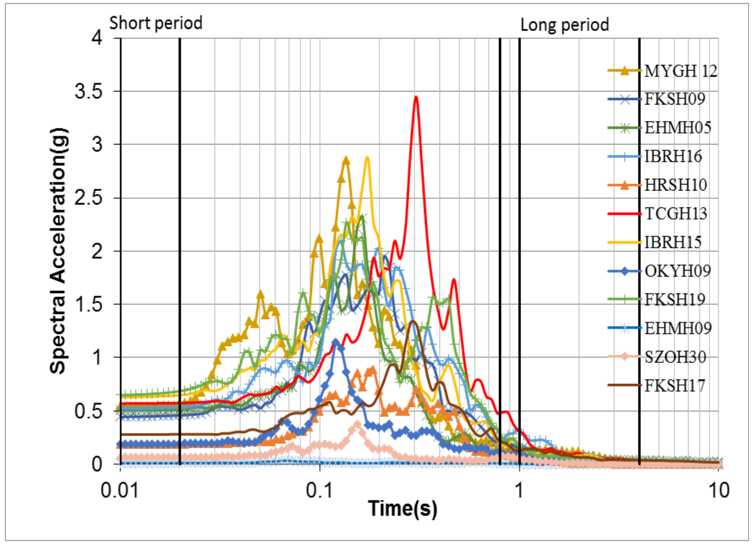
Site Classification based on 30 m

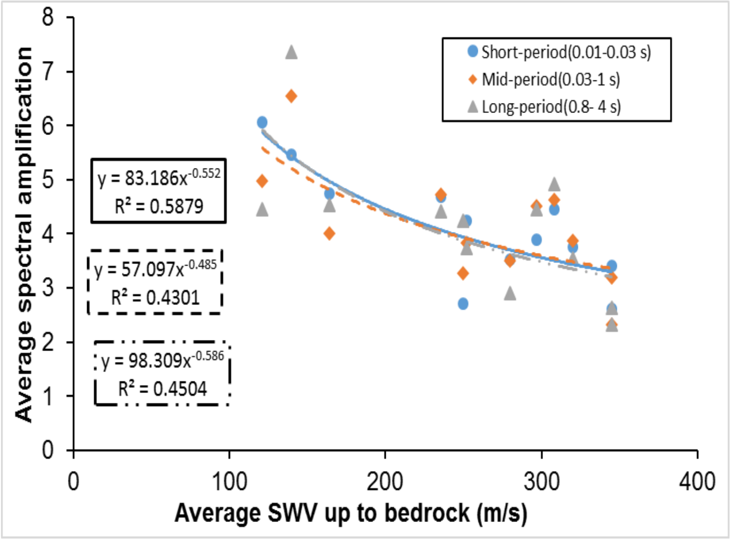
30 m Model works? – Recorded EQ data from Japan

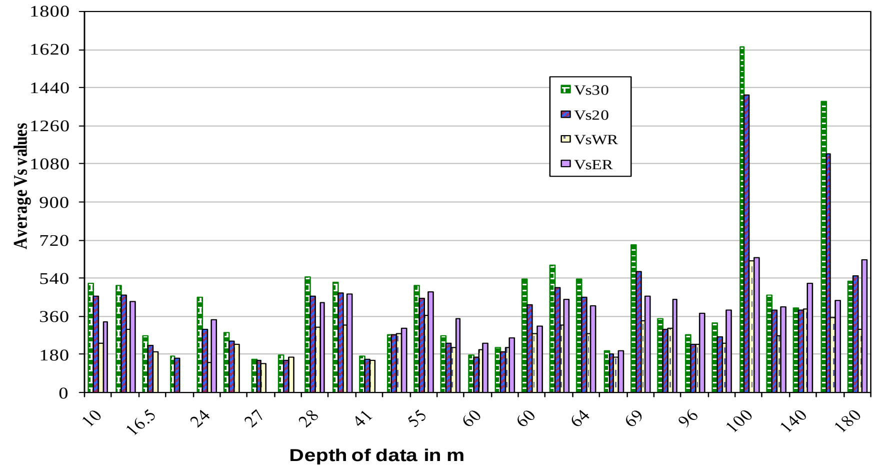


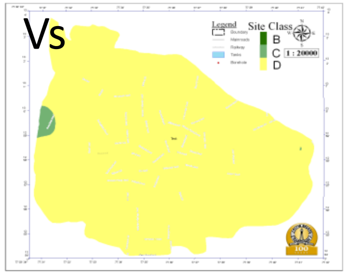


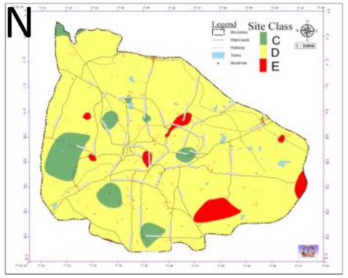












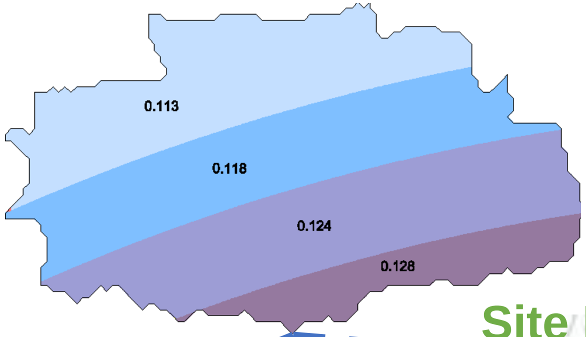
"Seismic Site Classification and Amplification of Shallow bedrock sites", Plos One, 13(12): e0208226. DOI. https://doi.org/10.1371/journal.pone.0208226.

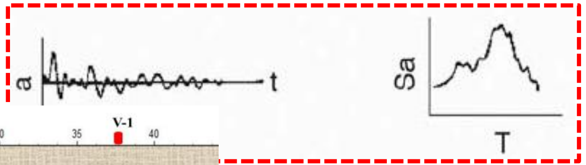
Site Classification based on Soil Thickness

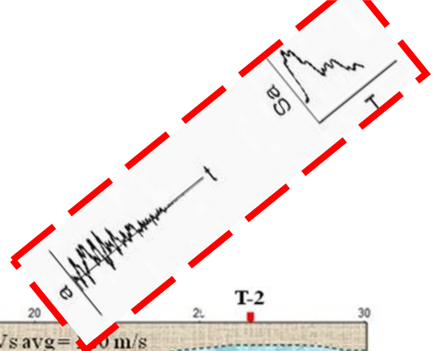
Site Characterization

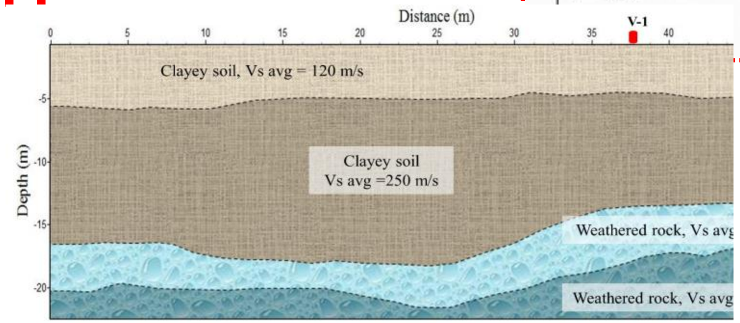
Rock PGA

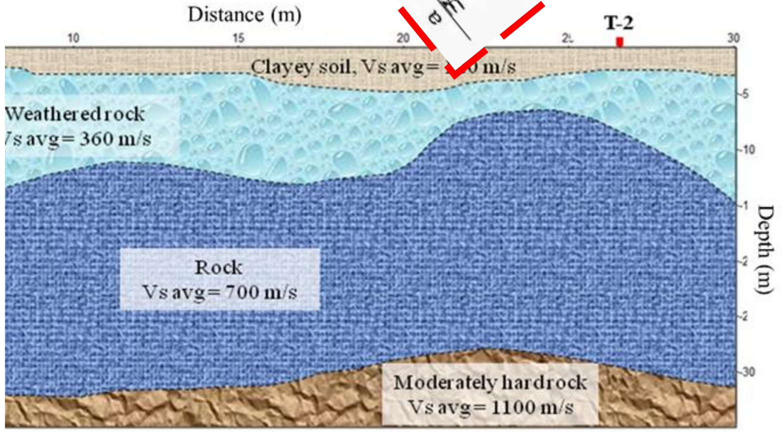
SHA







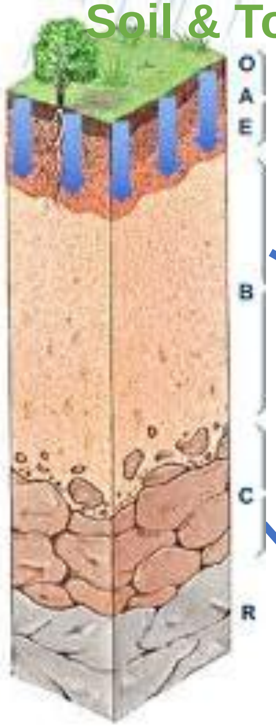


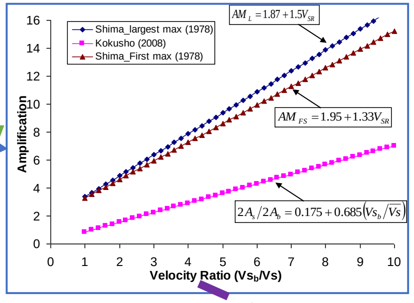


- ➢Bedrock Level Design Spectrum
- ➢ Zonation Maps at bedrock Level

Site Effects

Soil & Topography



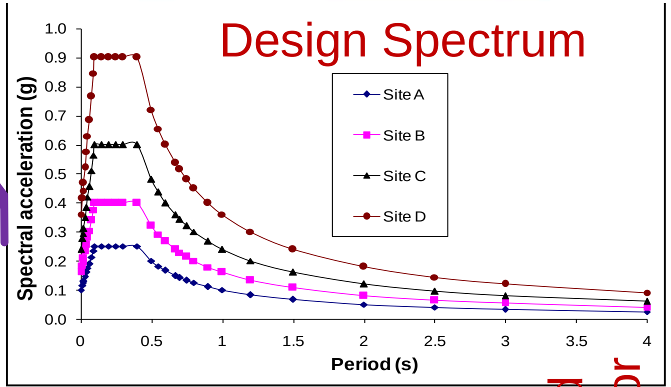


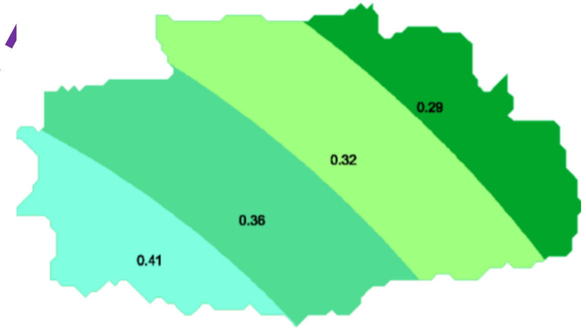
Amplification factor

Induced effects

Olympia, Washington, 2001

Design Spectrum



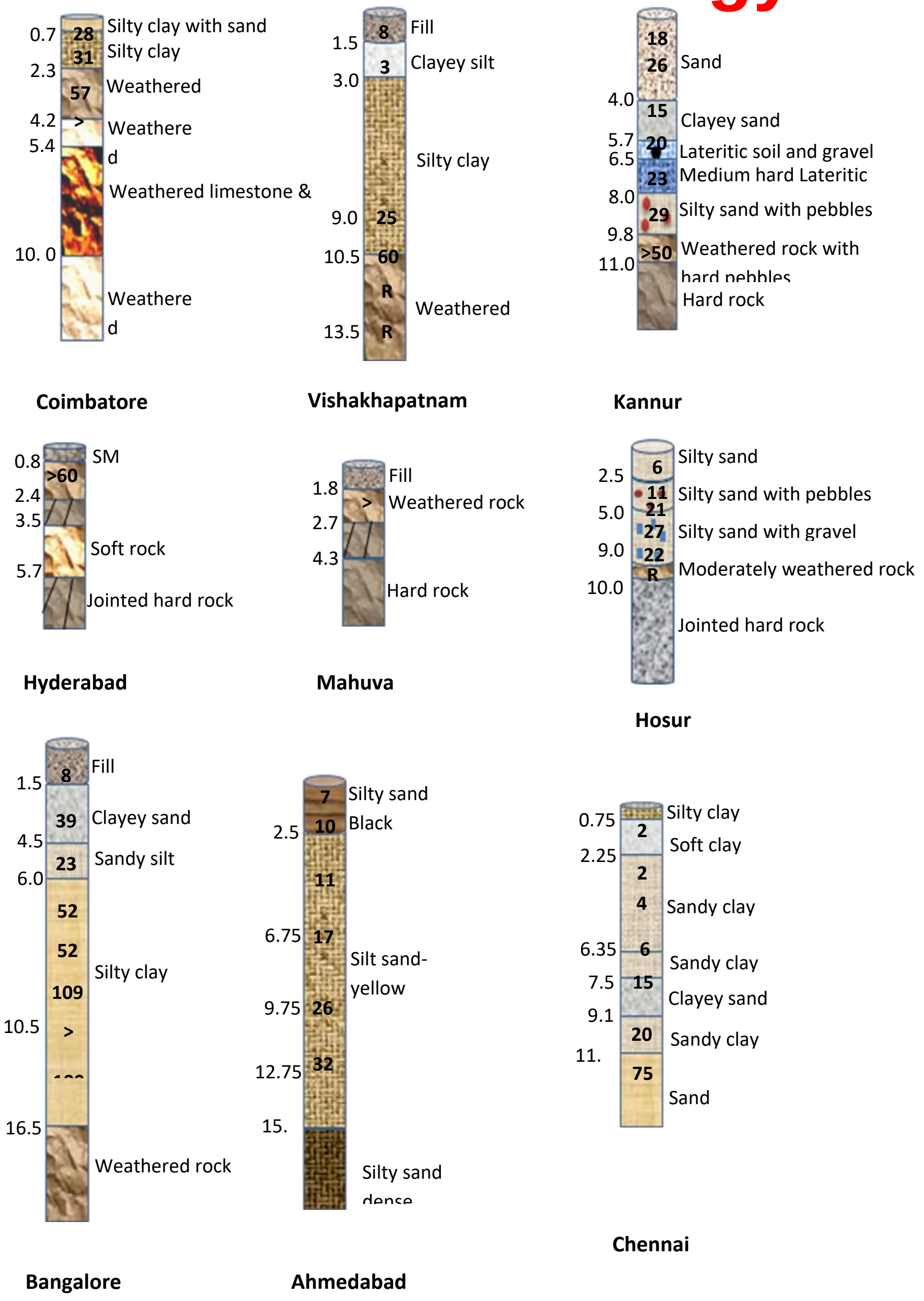


Zonation for/to Surface Hazard or Liquefaction or Landslide

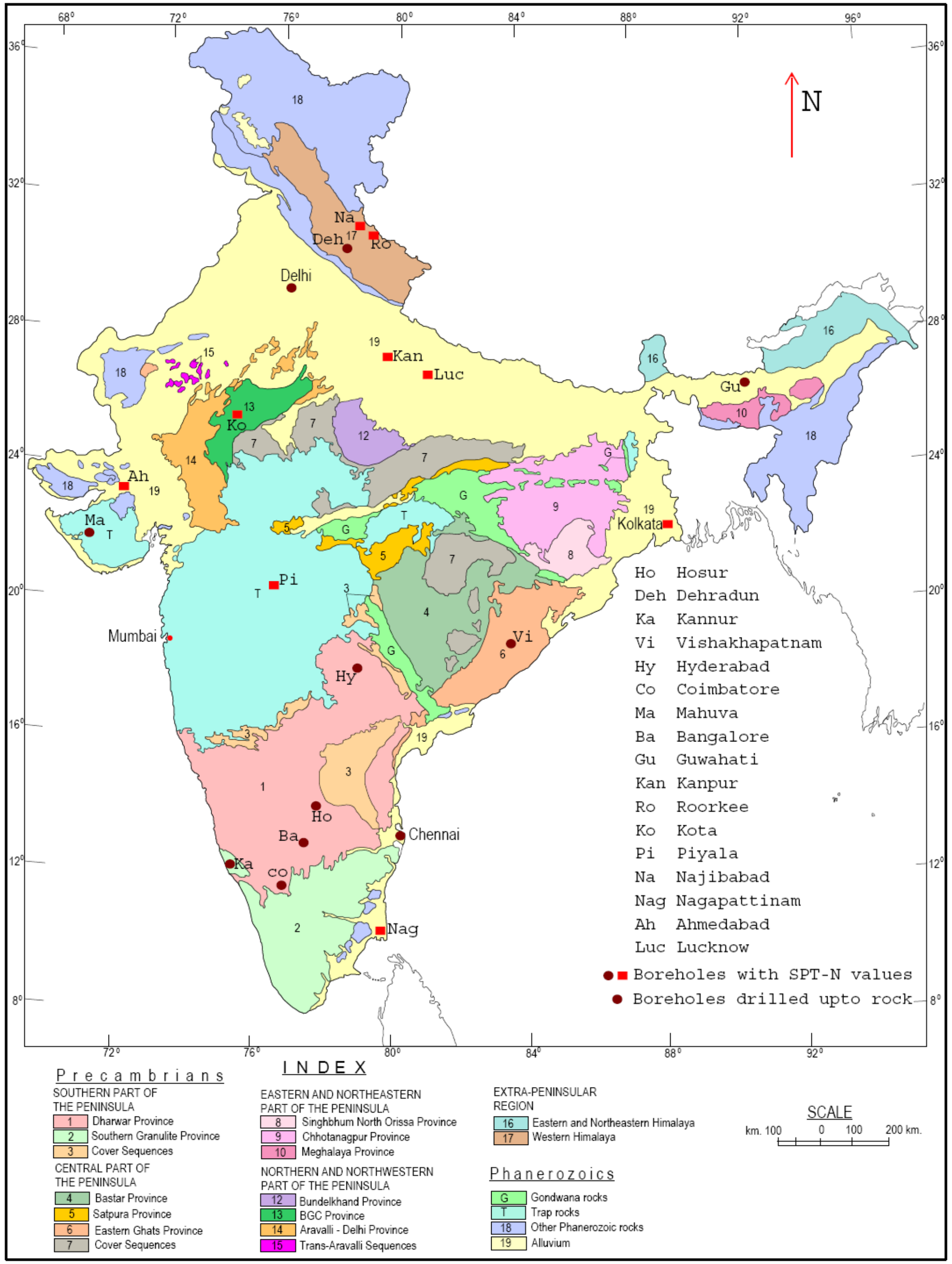
Site Characterization

- ❖Applicability & Validation of method & Model
- ❖Soil stiffness (Vs & ɣ)
- ❖Thickness
- ❖Comparison, Correlation & Relation
- ❖Soil behaviour dynamic model

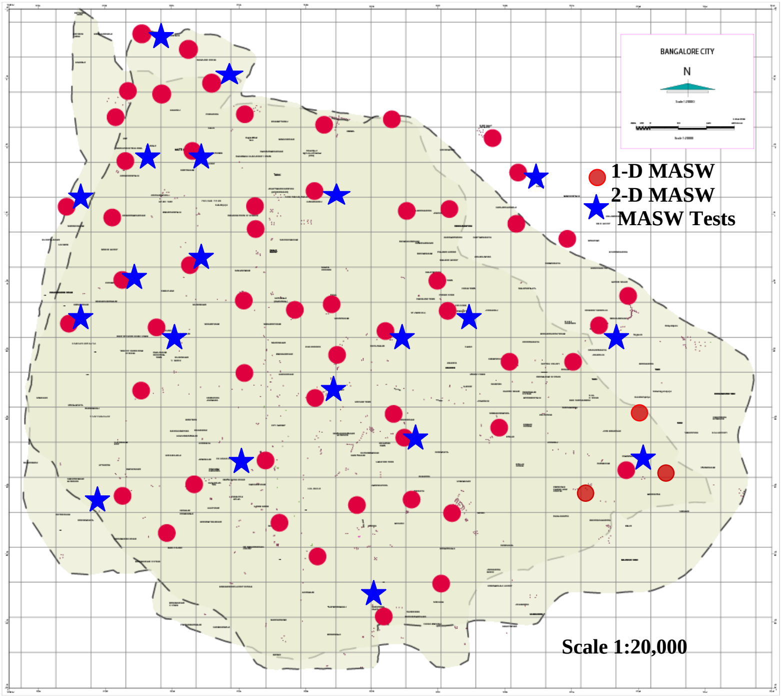
Indian Soil and Geology -South

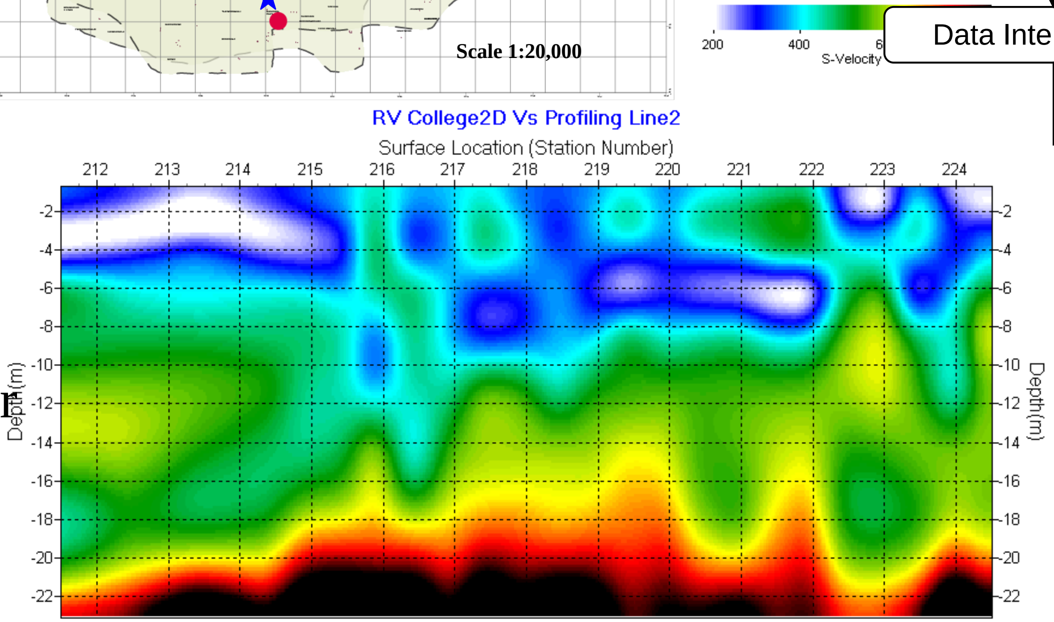


"Provisions for Geotechnical Aspects and Soil Classification in Indian Seismic Design Code IS-1893",
Disaster Advances, Vol. 7(3), 72-89.

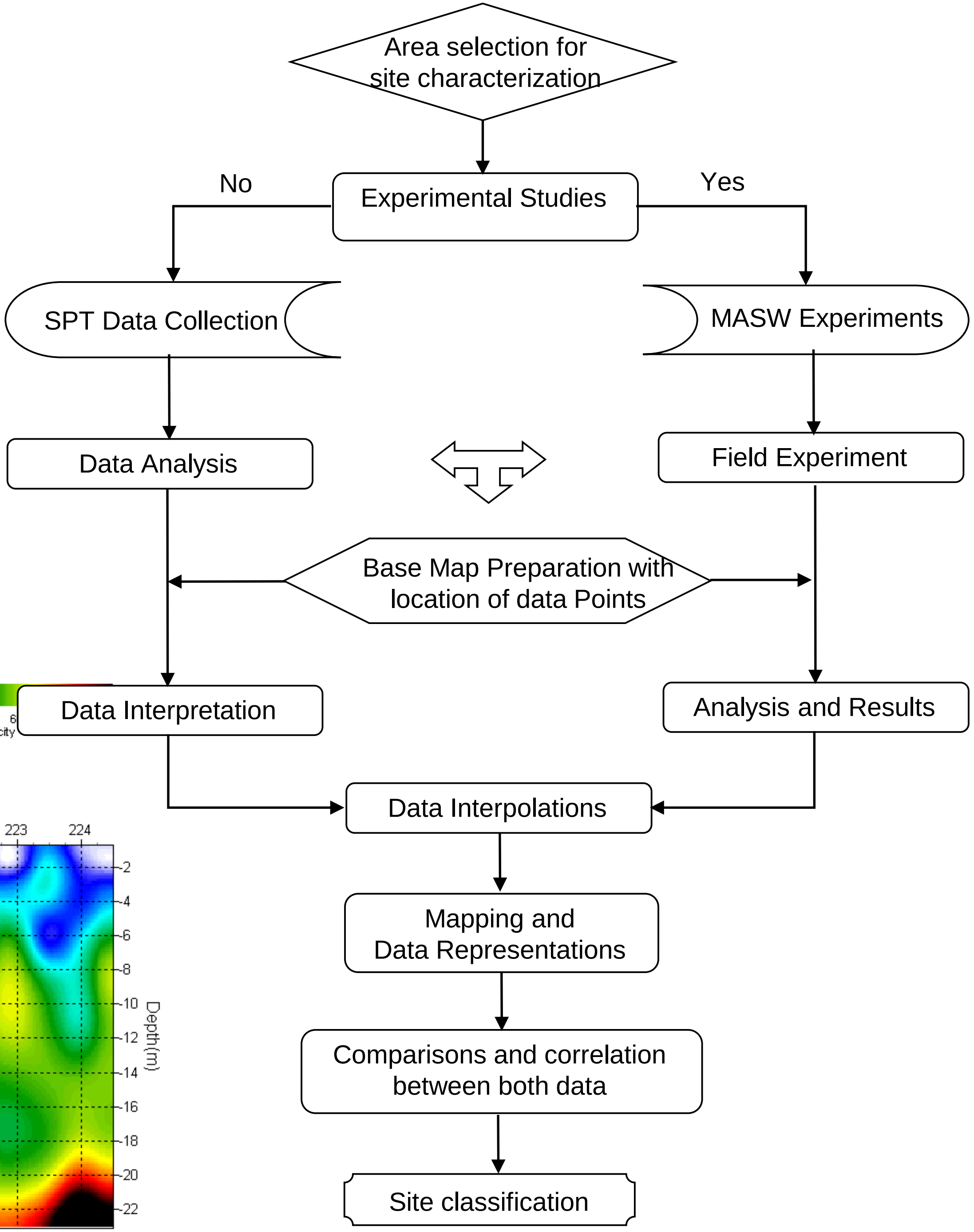


First Systematic Steps for site characterization

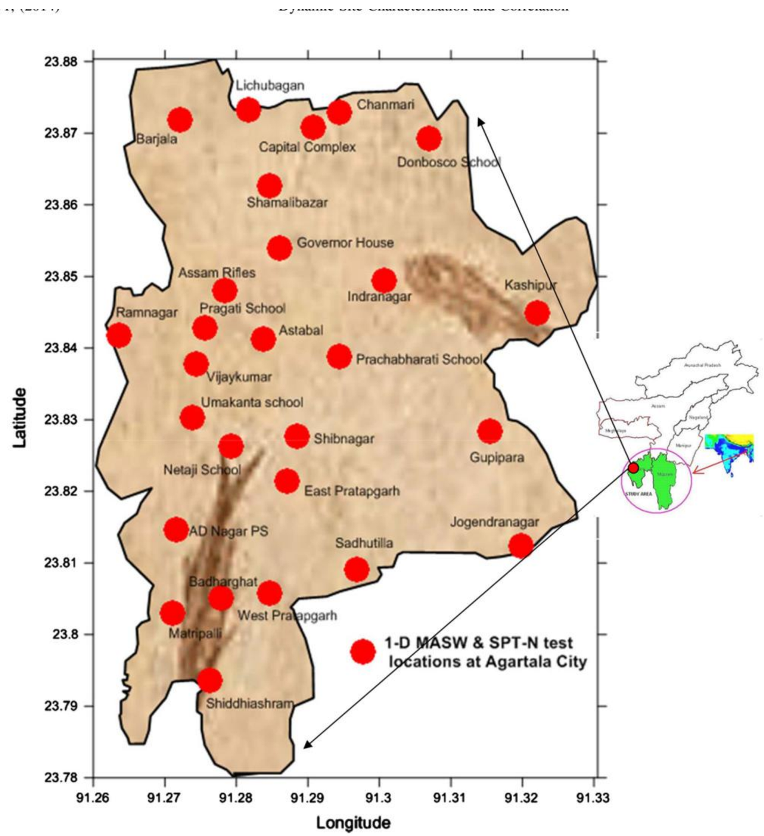




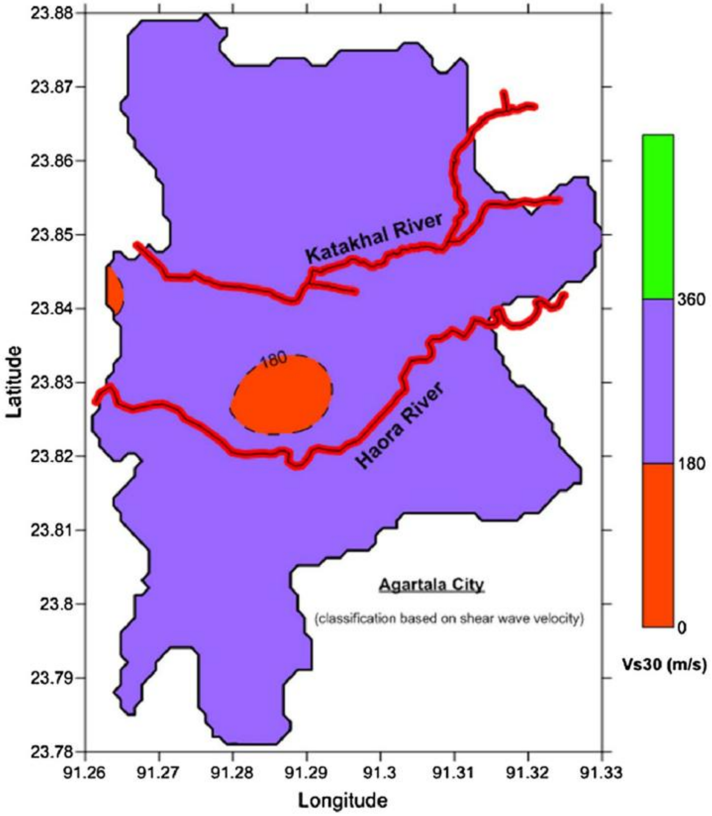
- Average shear wave velocity calculated for each 5m interval up to 30m depth
- Suitability of Vs^{30} for Indian shallow bedrock sites is questioned



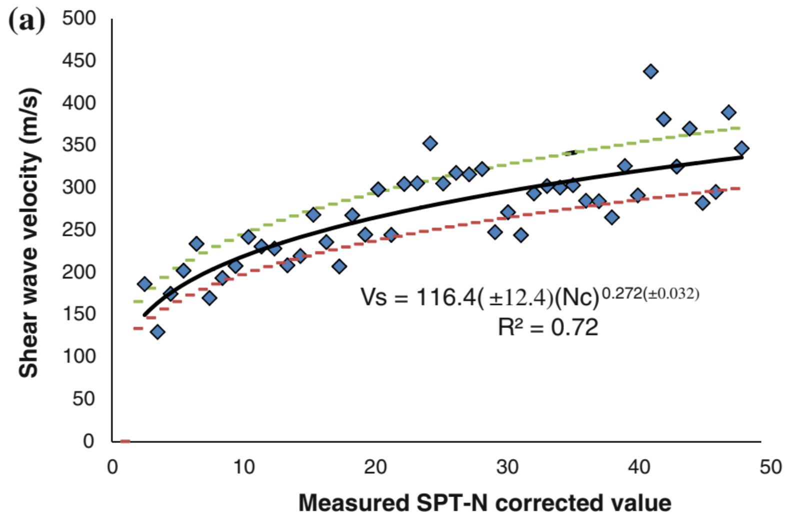
Studies for Agartala City



The study area – Agartala City



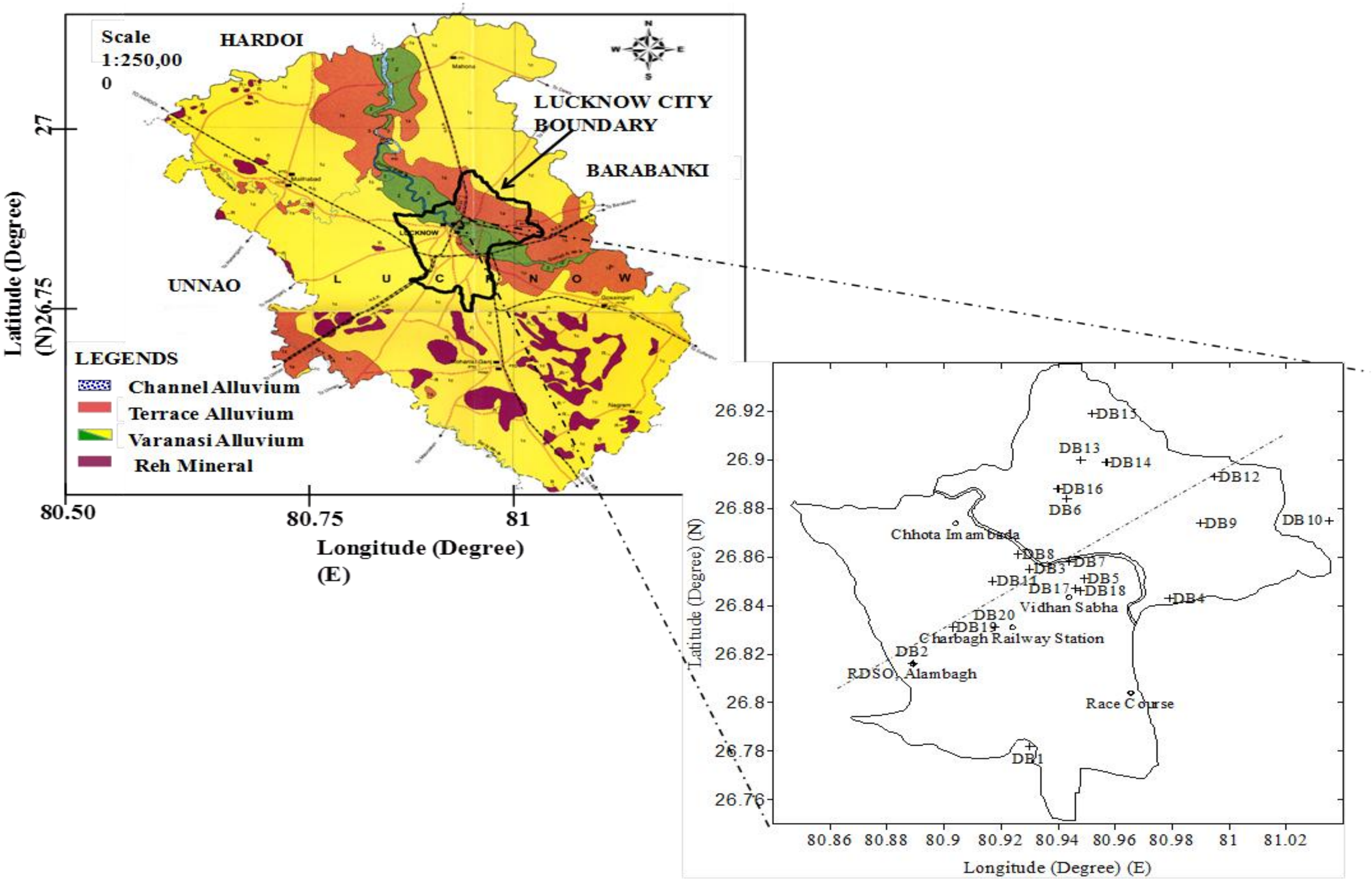
NEHRP classification based on average shear wave velocity (Vs30) for Agartala city

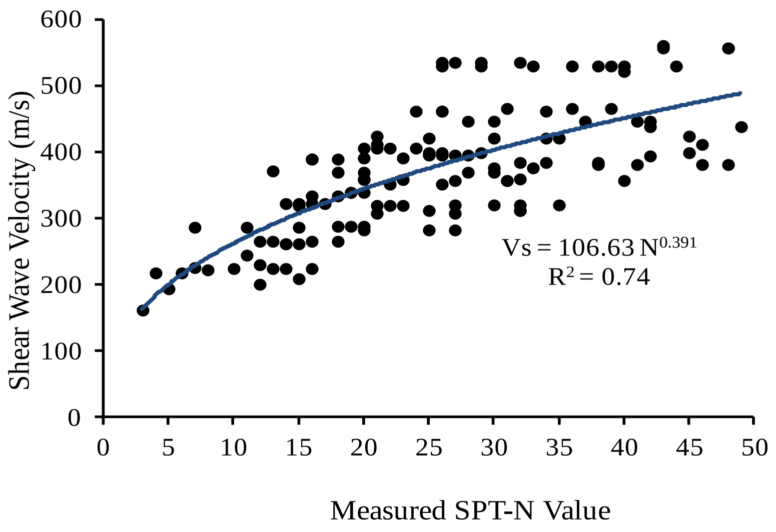


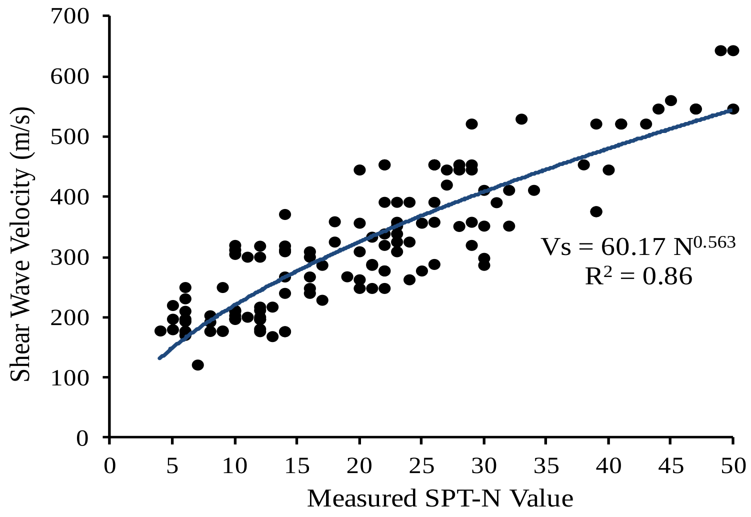
Correlations between Vs and a corrected SPT-N

Sil, A., & Sitharam, T. G. (2014). Dynamic site characterization and correlation of shear wave velocity with standard penetration test 'N'values for the city of Agartala, Tripura state, India. *Pure and Applied geophysics*, *171*(8), 1859-1876.

Studies for Lucknow City



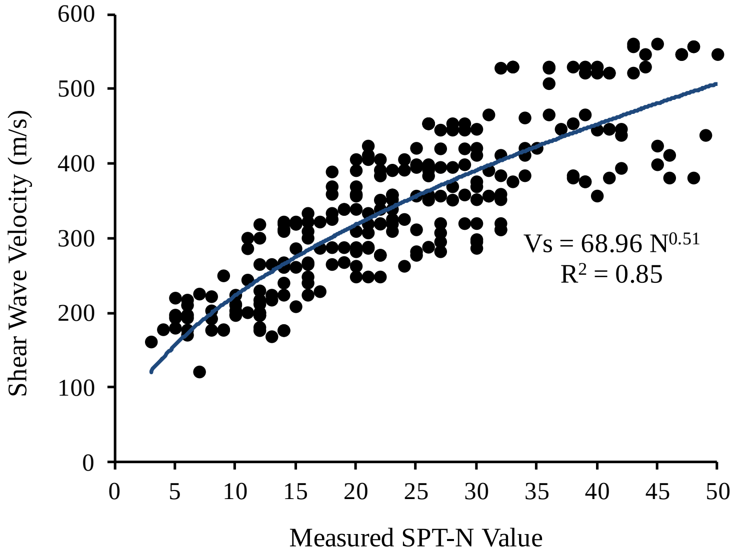




Clayey Soil

Sandy Soil

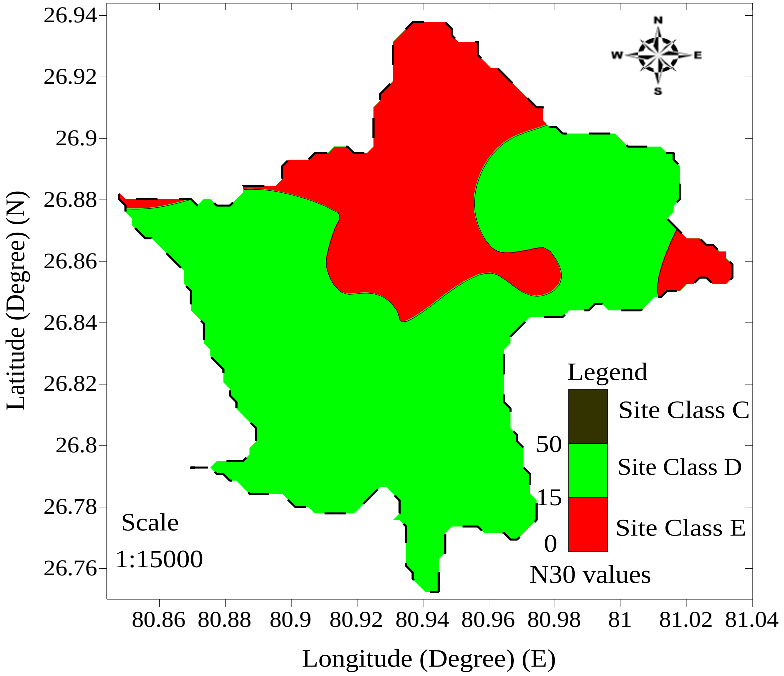
All Soil



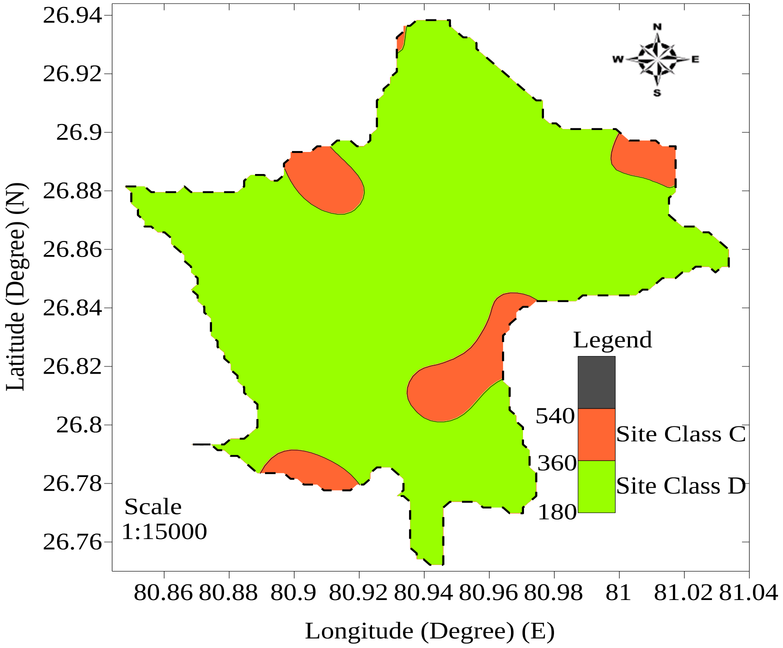
Anbazhagan P., Kumar Abhishek and Sitharam, T. G., (2013). Seismic Site Classification and Empirical Correlation between Standard Penetration Test N value and Shear wave velocity for Deep Soil Sites in Indo-Gangetic Basin, *Pure and Applied Geophysics,* 170 (3), 299-318.

Site classification of Lucknow

- Study area has been classified as per NEHRP (BSSC, 2003).
- Based on **N-SPT**, the entire Lucknow belong to **site class D and E** while based on **SWV** the city of Lucknow comes in **site class C and D**

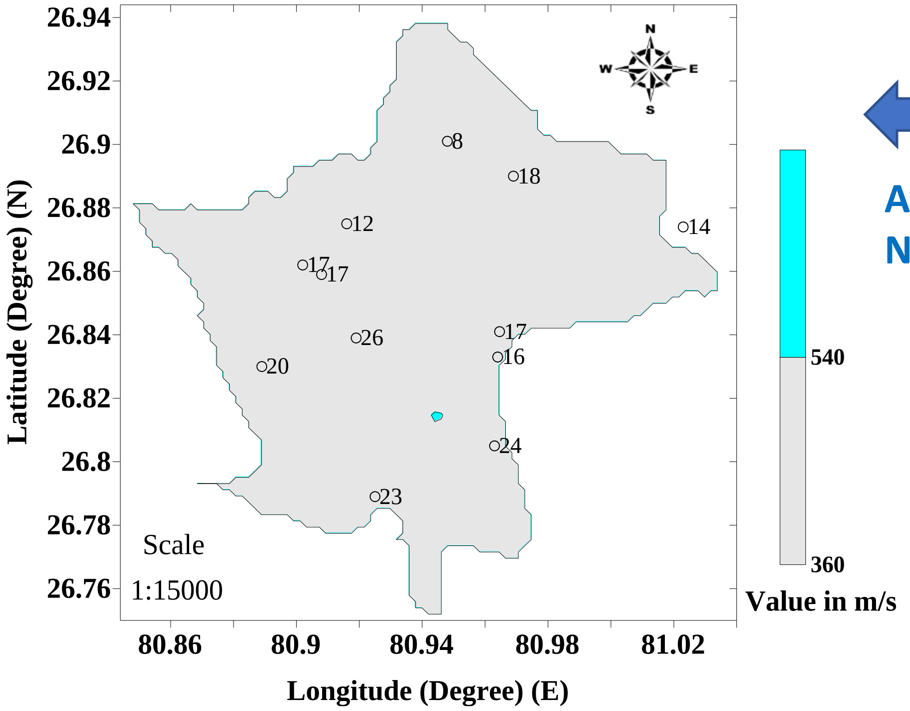


Site classification based on 30 m average N-SPT value



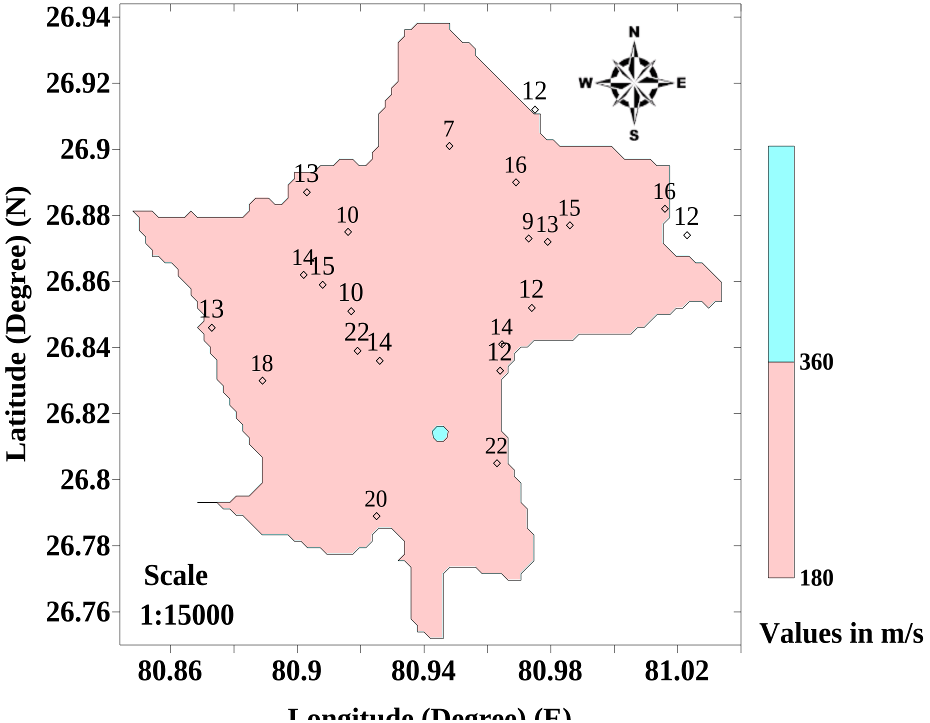
Site classification based on 30 m average SWV values

Anbazhagan P., Kumar Abhishek and Sitharam, T. G., (2013). Seismic Site Classification and Empirical Correlation between Standard Penetration Test N value and Shear wave velocity for Deep Soil Sites in Indo-Gangetic Basin, *Pure and Applied Geophysics*, 170 (3), 299-318.



Average Vs up to 760 m/s and number shows average N values up to the N value of 50

Average Vs up to 360 m/s and number shows average N values up to the N value of 30



Anbazhagan P., Kumar Abhishek and Sitharam, T. G., (2013). Seismic Site Classification and Empirical Correlation between Standard Penetration Test N value and Shear wave velocity for Deep Soil Sites in Indo-Gangetic Basin, *Pure and Applied Geophysics,* 170 (3), 299-318.

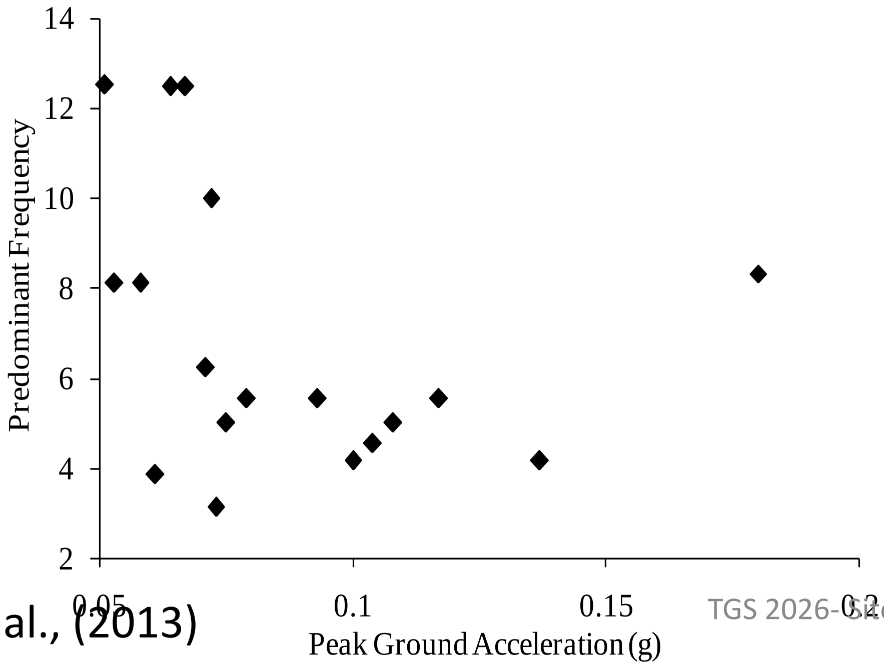
Site response study for Lucknow

- Local soil alters the bedrock motion.
- Solely govern by ground motion characteristics at bedrock.
- **Standard ground motions** (1985 Mexico, 1989 Loma Prieta) or **synthetic ground motions**, in **case bedrock motion is absent**.
- Ground motion characteristics which effect the soil response results are **amplitude, frequency content and duration**.
- **Multiple Ground motions** based on rock hazard values obtained from DSHA and **amplitude, frequency content and duration** are indentified and used for site response analysis

Ref: Sitharam et al., (2013)

Site response study for Lucknow

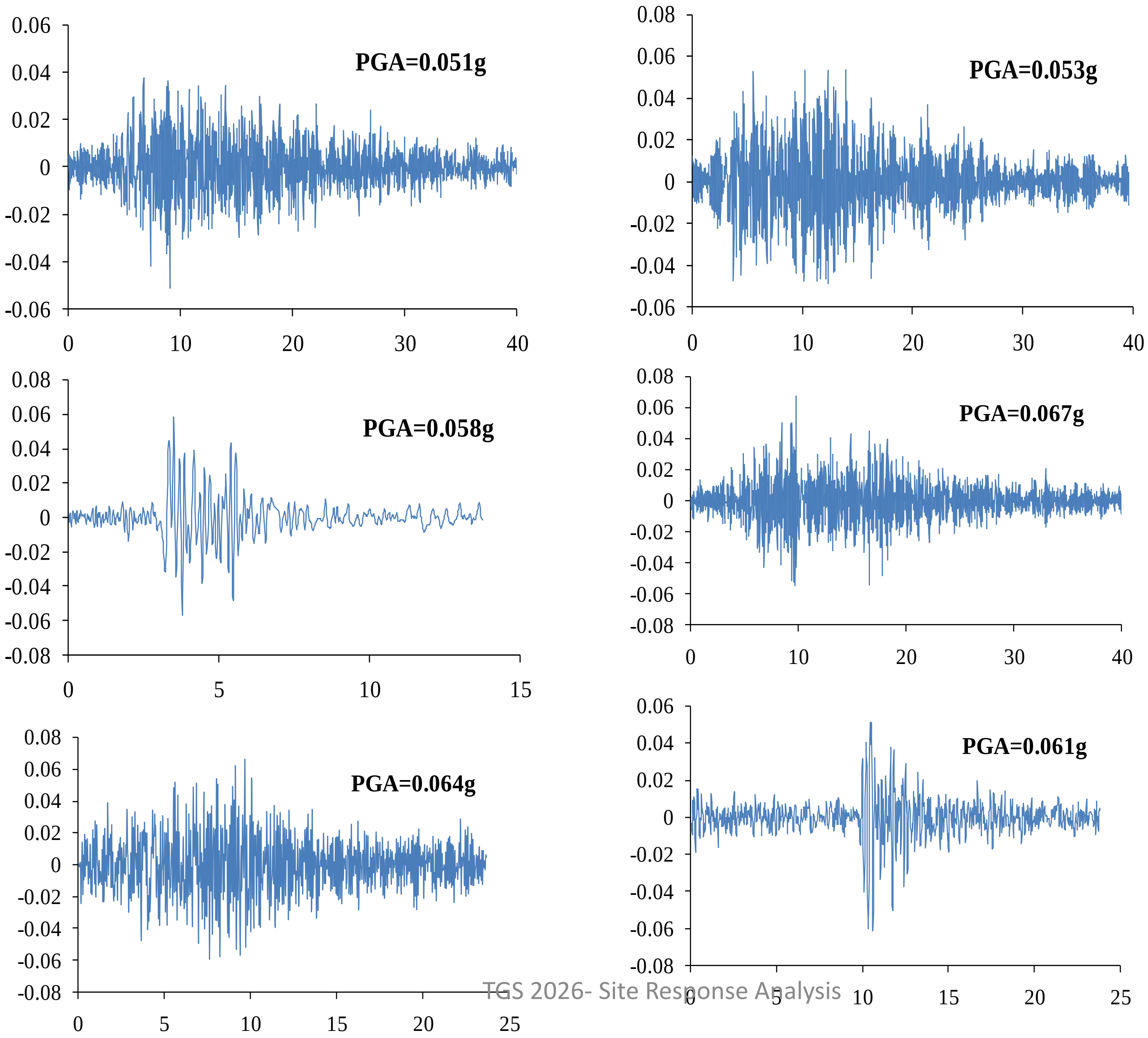
- The bedrock PGA range obtained from seismic hazard analysis has been divided into 4 classes namely; **i) 0.05-0.07g, ii) 0.07g -0.09g, iii)0.09g-0.12g, iv) >0.12g.**
- **18 recorded ground motions** selected from various earthquakes in **Himalayan region from 1980 Dharmsala to 2011 Sikkim earthquakes**
- Ground motions have been selected to cover **all possible combinations of frequency, amplitude and duration** in the base motion.



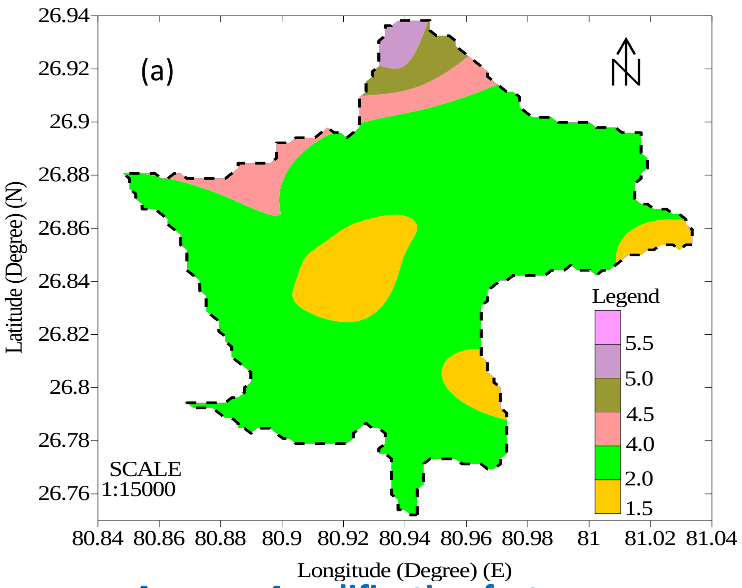
No.	Earthquake	(Mw)	Station Name	PGA (g)	Significant duration (seconds)	Predominant Frequency (Hz)
1.	1991 Uttarkashi	6.8	Srinagar (L)	0.051	25.54	12.54
2.	1991 Uttarkashi	6.8	Rudraprayag (L)	0.053	23.84	8.13
3.	1986 Dharmsala	5.5	Baroh (L)	0.058	4.32	8.13
4.	1988 India-Bangladesh	5.8	Umsning (T)	0.061	14.54	3.85
5.	1988 India-Burma	6.8	Mawsyram (T)	0.064	18.18	12.50
6.	1991 Uttarkashi	6.8	Srinagar (T)	0.067	25.38	12.50
7.	1999 Chamoli	6.5	Joshimath (L)	0.071	11.18	6.25
8.	1991 Uttarkashi	6.8	Tehri (L)	0.073	14.14	3.12
9.	1991 Uttarkashi	6.8	Purola (L)	0.075	13.58	5.00
10.	1988 India-Burma	6.8	Umrongso (T)	0.079	32.14	5.55
11.	1997 India-Burma	6.8	Shillong (T)	0.072	18.79	10.00
12.	1991 Uttarkashi	6.8	Purola (T)	0.093	11.70	5.55
13.	1991 Uttarkashi	6.8	Koteshwar (L)	0.10	14.16	4.17
14.	1988 India-Burma	6.8	Mawphlang (T)	0.104	35.58	4.54
15.	1988 India-Bangladesh	5.7	Nongkhlaw (L)	0.108	24.20	5.00
16.	1991 Uttarkashi	6.8	Ghansiali (T)	0.117	17.70	5.55
17.	1988 India-Burma	6.8	Nongkhlaw (L)	0.137	13.52	4.17
18.	2010 Bageshwar	4.6	Kapkot (L)	0.180	5.18	8.33

Ref: Sitharam et al., (2013)

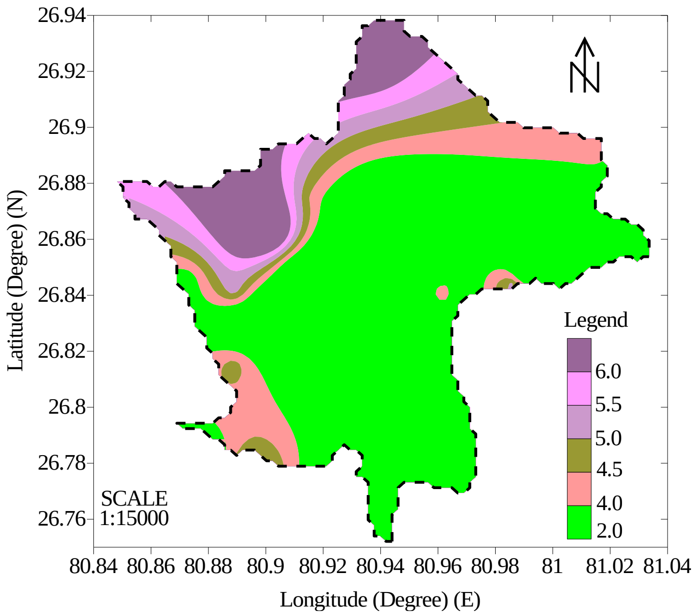
Selected Ground Motions for class 1



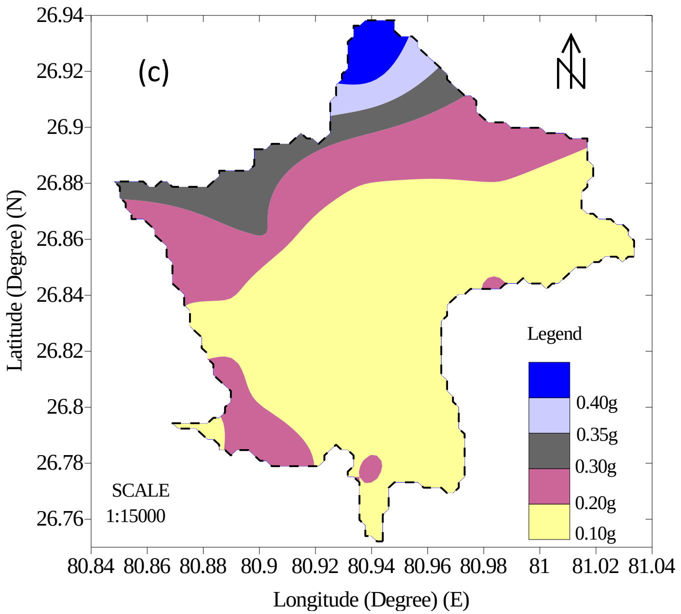
Ref: Sitharam et al., (2013)

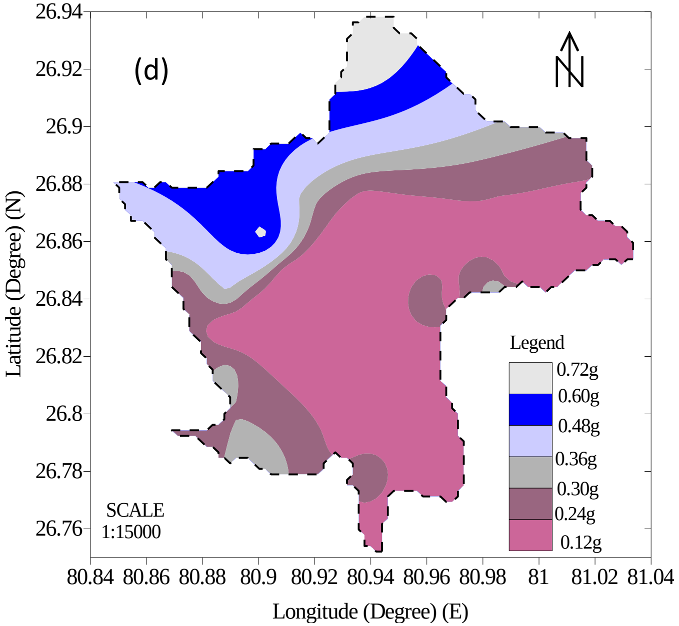


Average Amplification factor



Maximum Amplification factor



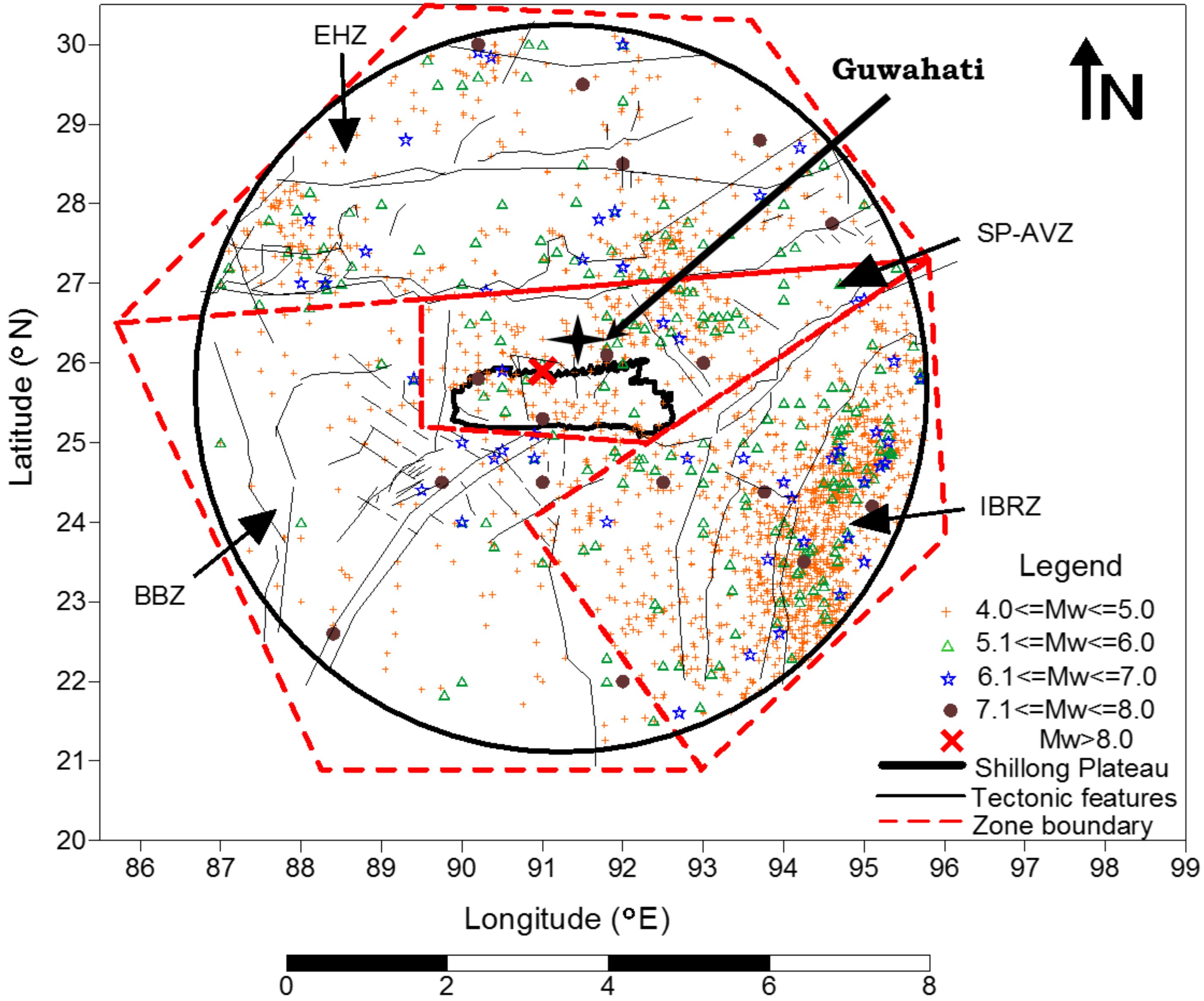


Ref: Sitharam et al., (2013)

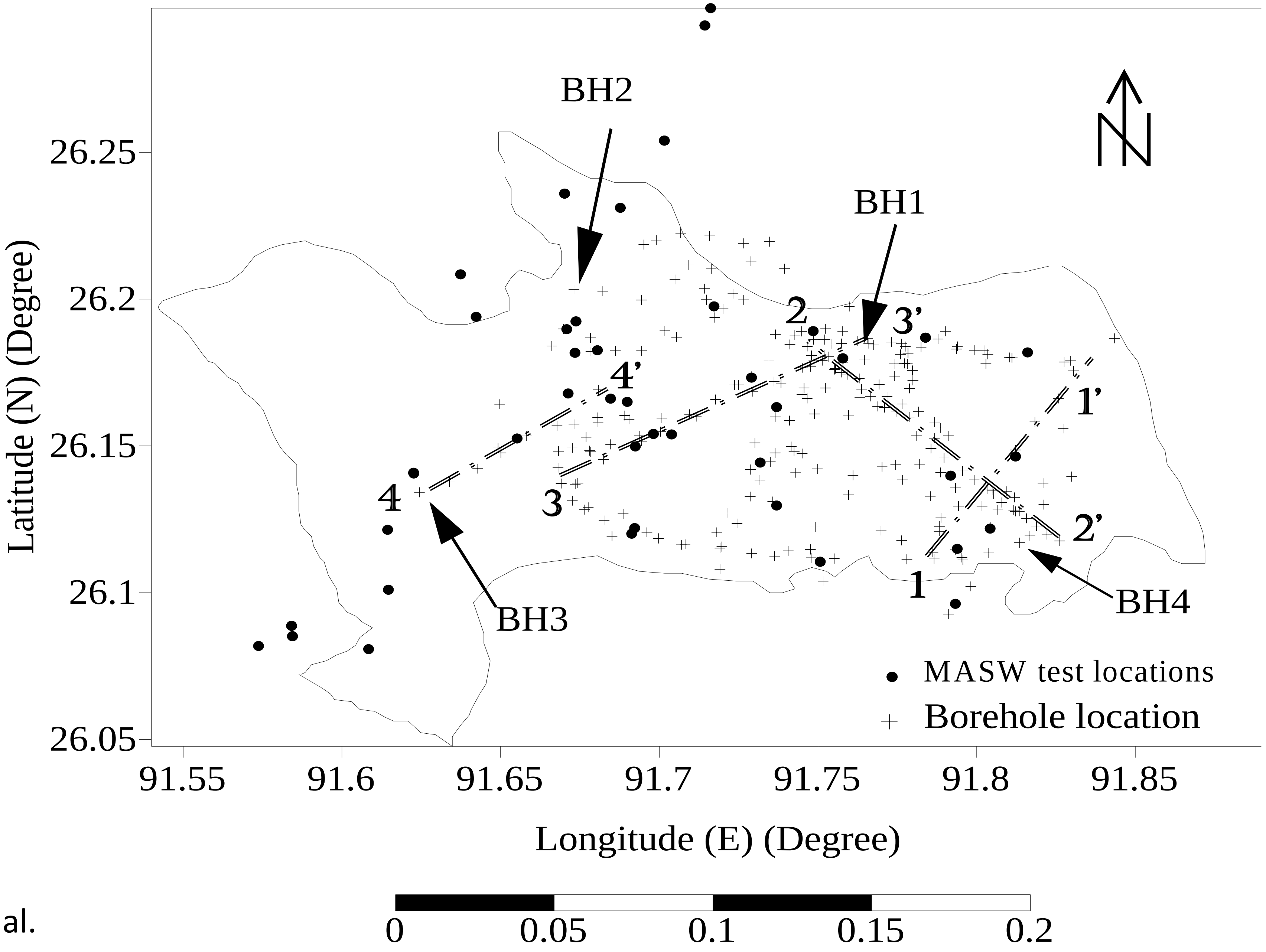
Surface PGA map based on average amplification factor

Surface PGA map based on maximum amplification factor

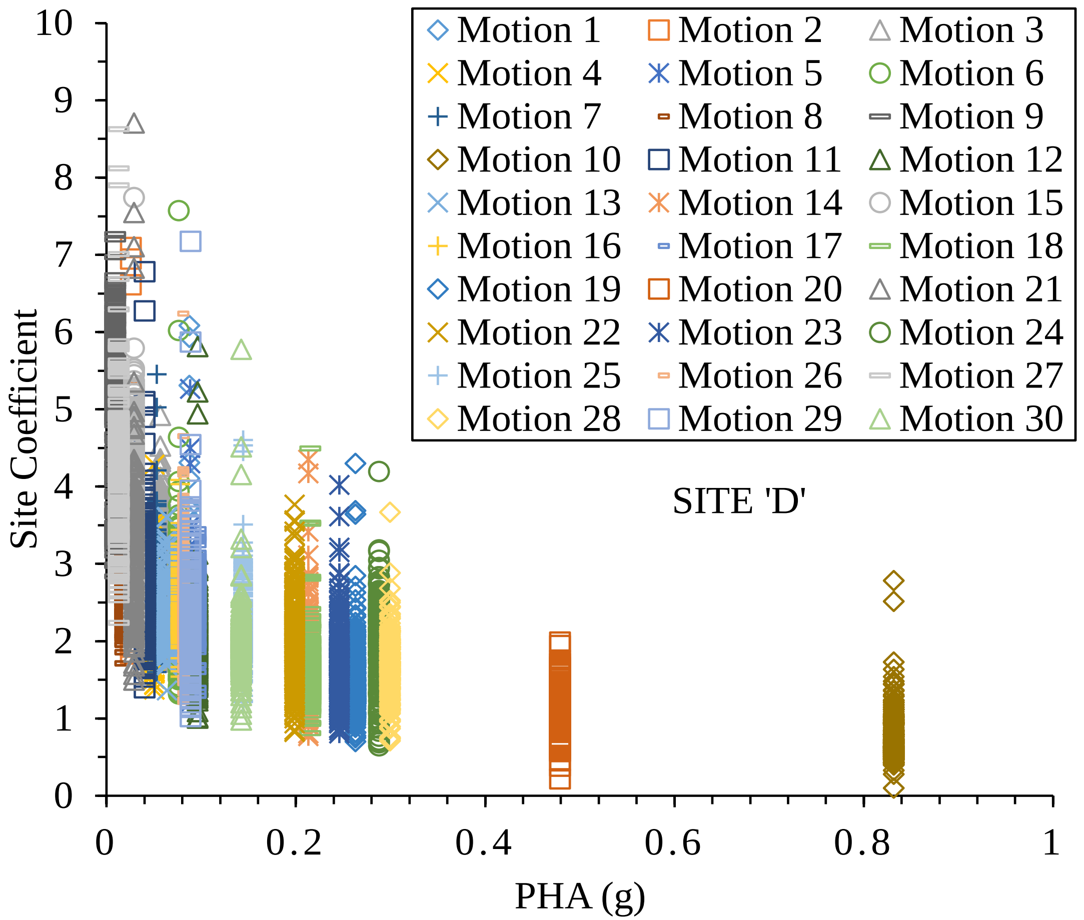
Subsoil of Guwahati

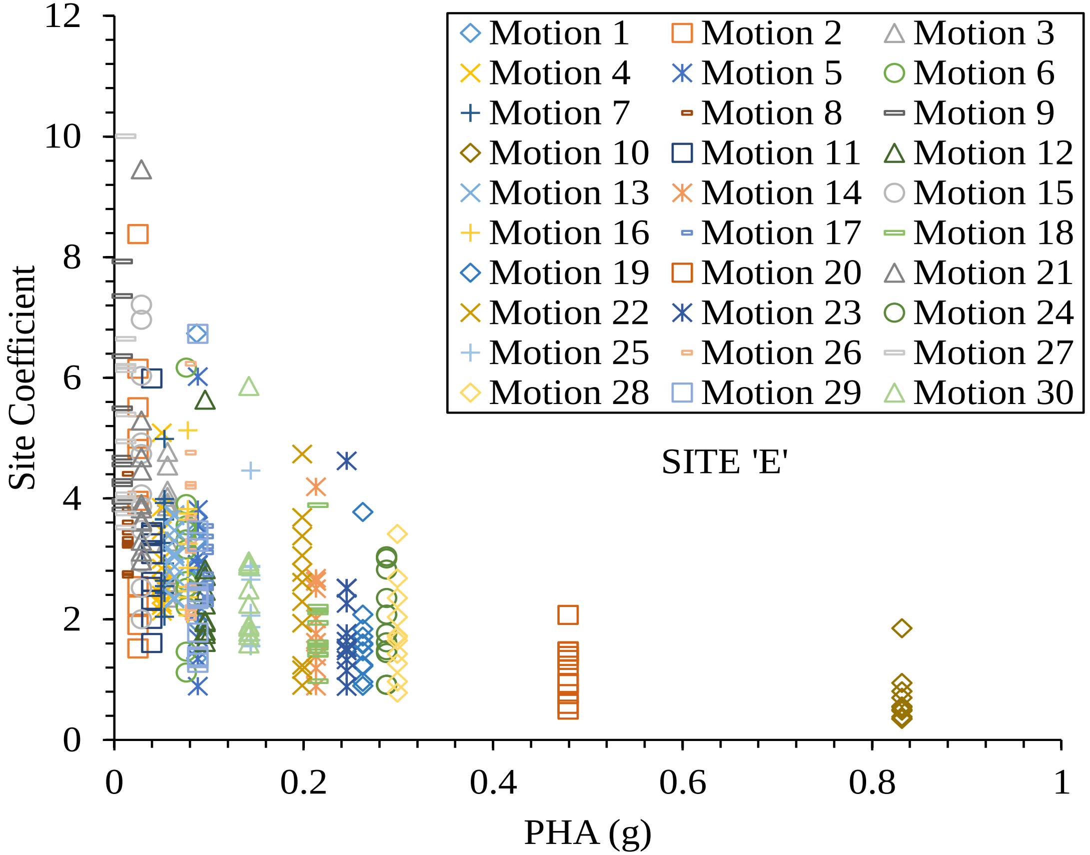


Ref: Kumar et al. (2018)

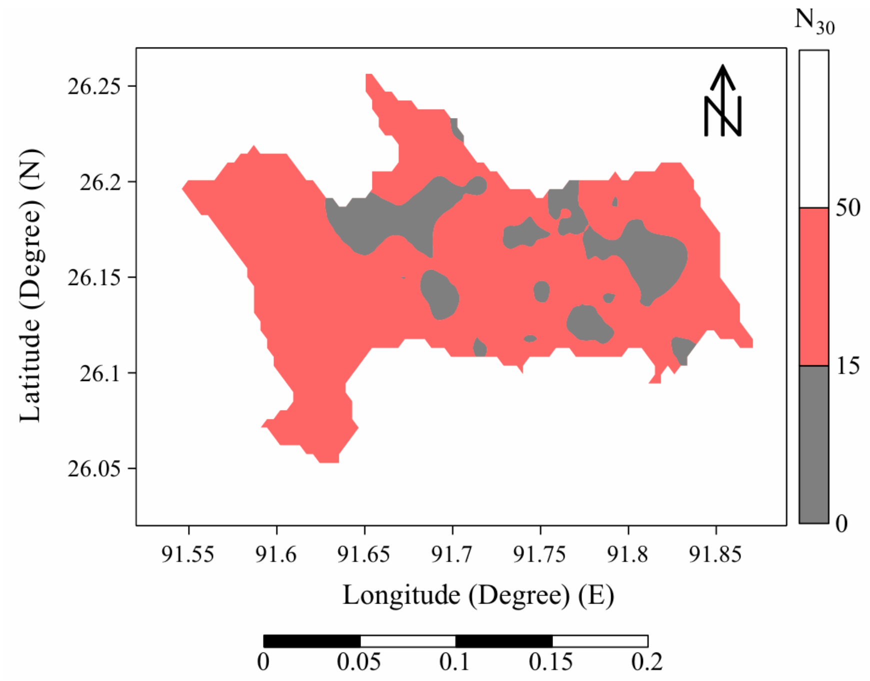


Ref: Kumar et al. (2018)





Ref: Kumar and Haldar (2020)



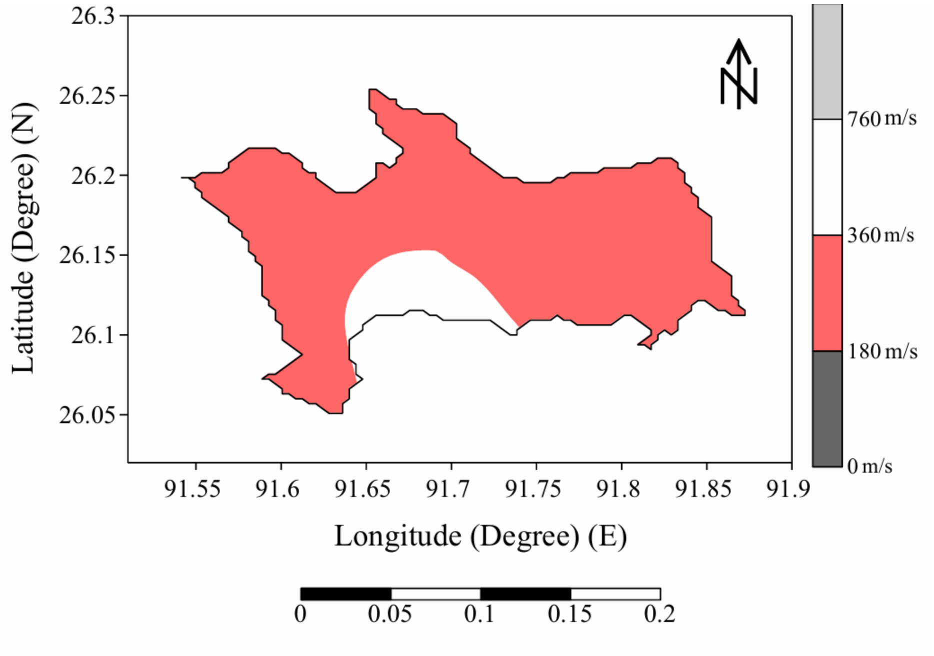


Figure 7
V_{S30}-based seismic site classification map of Guwahati

Ref: Kumar and Haldar (2020)

Field investigations in Madhubani and Darbhanga regions

Ref: Chatterjee et al. (2026)

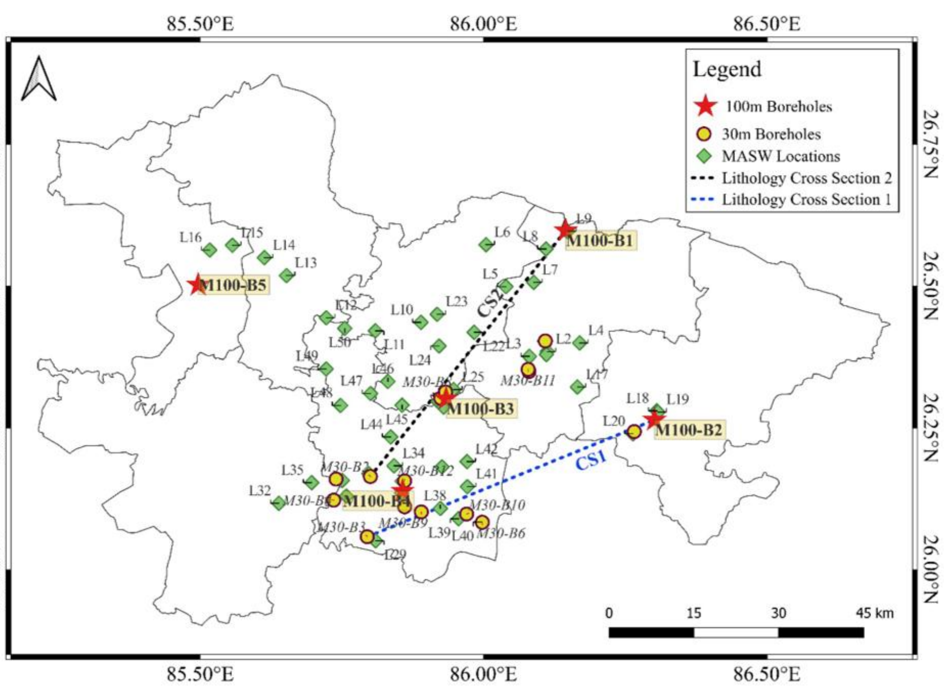


Fig. 4 Map showing different depth boreholes along with the cross-sections across the study area considered for the lithology study

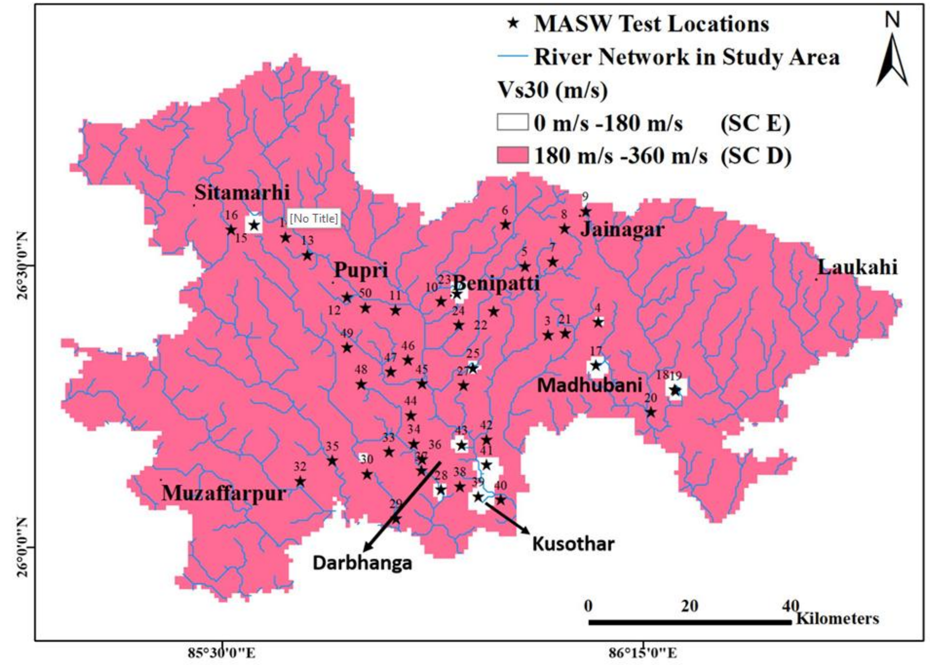


Fig. 8 Site classification map based on V_{s30} according to NEHRP

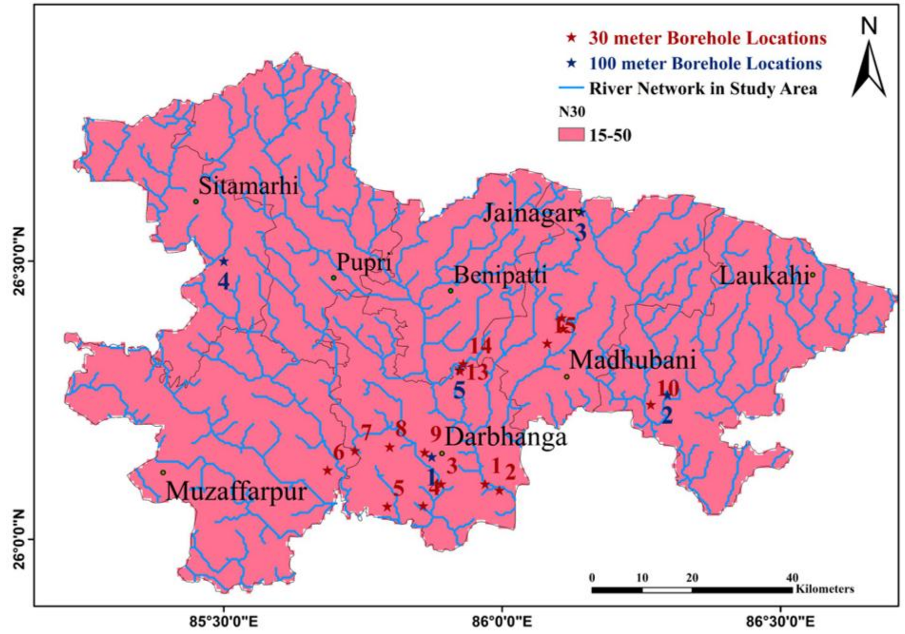
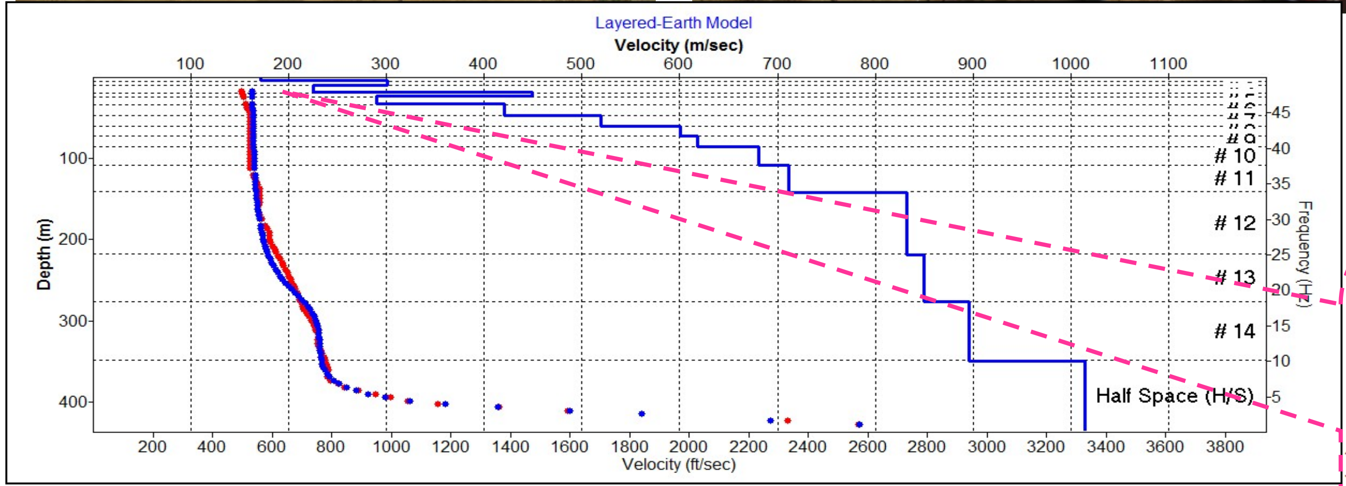
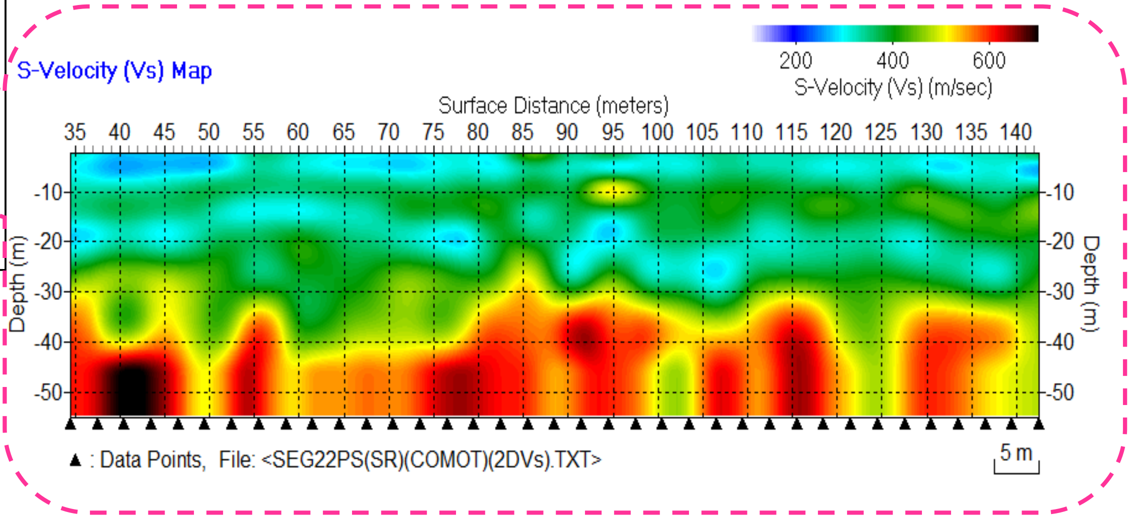


Fig. 10 Site classification map based on N_{30} according to NEHRP

Deep shear wave velocity measurement @ NPP GHAVP -1&2

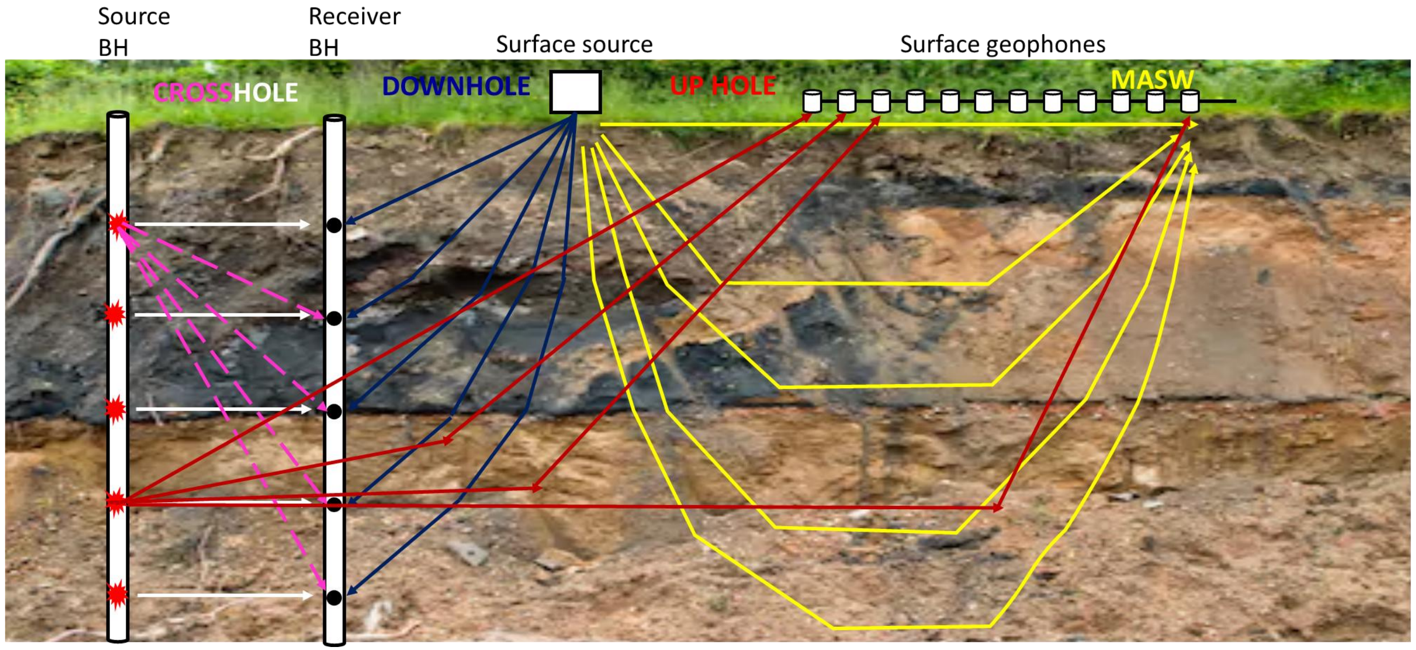
Ketan Bajaj and P Anbazhagan (2019). "[Seismic site classification and correlation between Vs and SPT-N for deep soil sites in Indo-Gangetic Basin]" Journal of Applied Geophysics, 163, 55-72. DOI: https://doi.org/10.1016/j.jappgeo.2019.02.011.

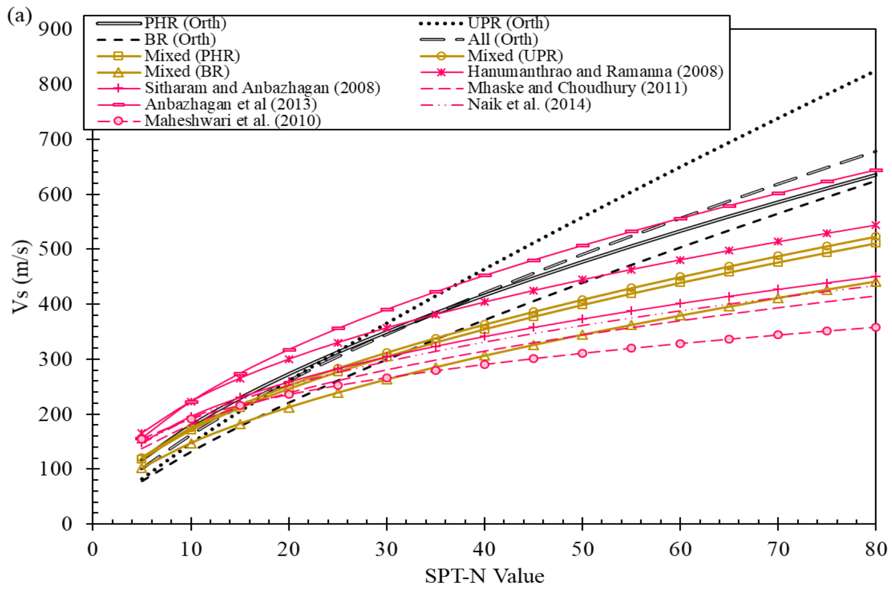


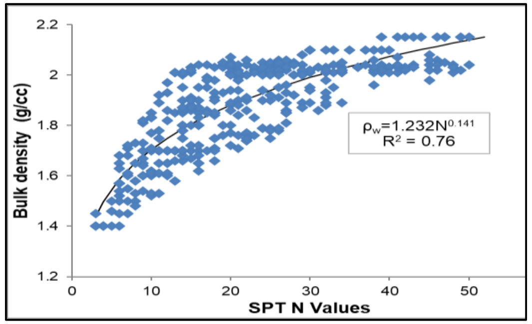


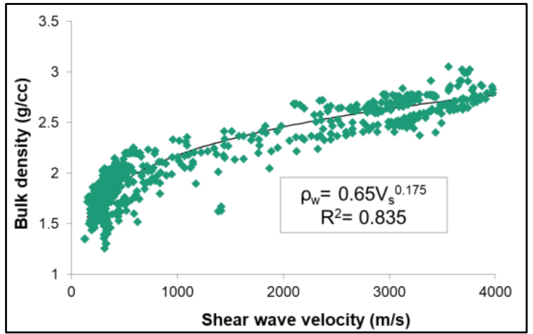
Geophysical and Site-specific Testing at BRNS & NPCIL

Correlations & model for Indian Soil

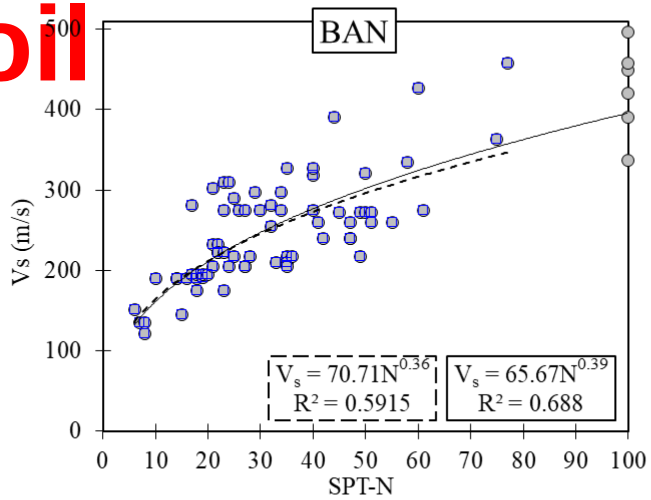


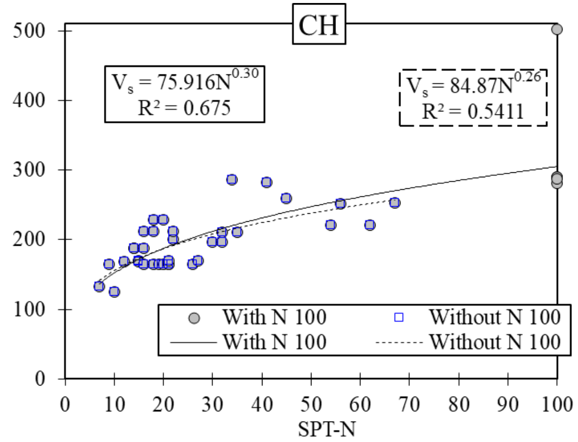


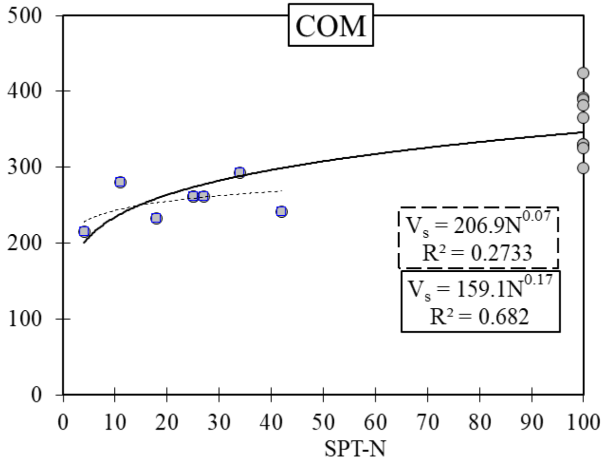




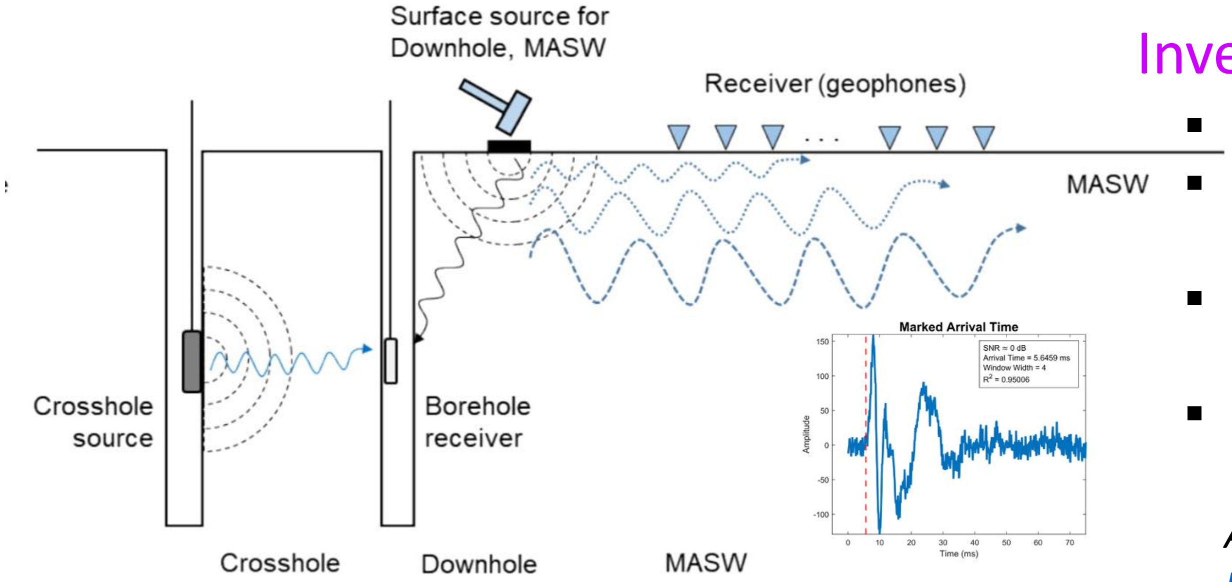
Anbazhagan P, Anjali Uday, Sayed SR Moustafa and Nassir S.N. Al-Arifi (2016). "Correlation of Densities with Shear Wave Velocities & SPT N Values", Journal of Geophysics and Engineering, 13, 320-341. doi:10.1088/1742-2132/13/3/320.







Seismic Borehole Tests – Research

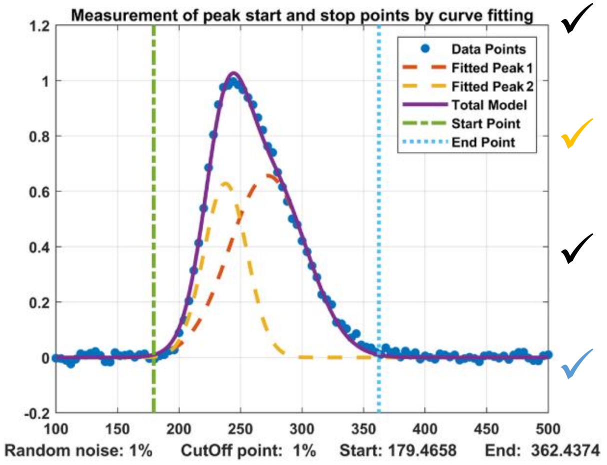


Invention of Raypath Analysis in Downhole Tests

- Straight vs refracted raypath: < 1% difference
- Average Vs can be reliably calculated without detailed inversion
- Single measurement at different depths is sufficient for site class
- Different Vs models from DH result in similar Vsz as depth increases.

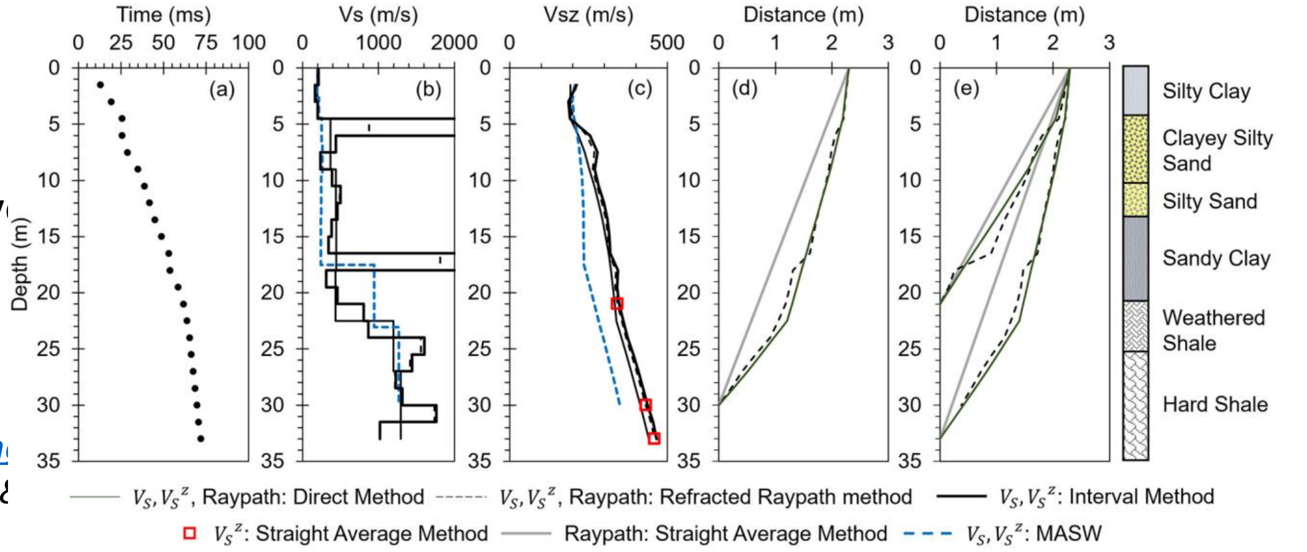
Ayush Kumar and P Anbazhagan,(2025)"[Influence of Subsurface Refraction and Wave Travel Path on the Estimation of Average Vs Profiles from the Seismic Downhole Test](http://doi.org/10.1002/nsg.70009)" Near Surface Geophysics.23:229-251 DOI: http://doi.org/10.1002/nsg.70009

Novel P-wave & **S-wave** Arrival Time Picking



- ✓ Eliminates manual judgement and bias
- ✓ Iterative Curve Fitting (Gaussian) for P-wave
- ✓ Bézier intersection for S-wave detection
- ✓ Robust to SNR −20 dB; eliminates human bias

Anbazhagan P and Sauvik Halder(2024) "[A Novel Algorithm for Identifying Arrival Times of P and S Waves in Seismic Borehole Surveys](https://doi.org/10.1016/j.cageo.2024.105746)" Computers & Geosciences. 194, 105746, DOI: https://doi.org/10.1016/j.cageo.2024.105746



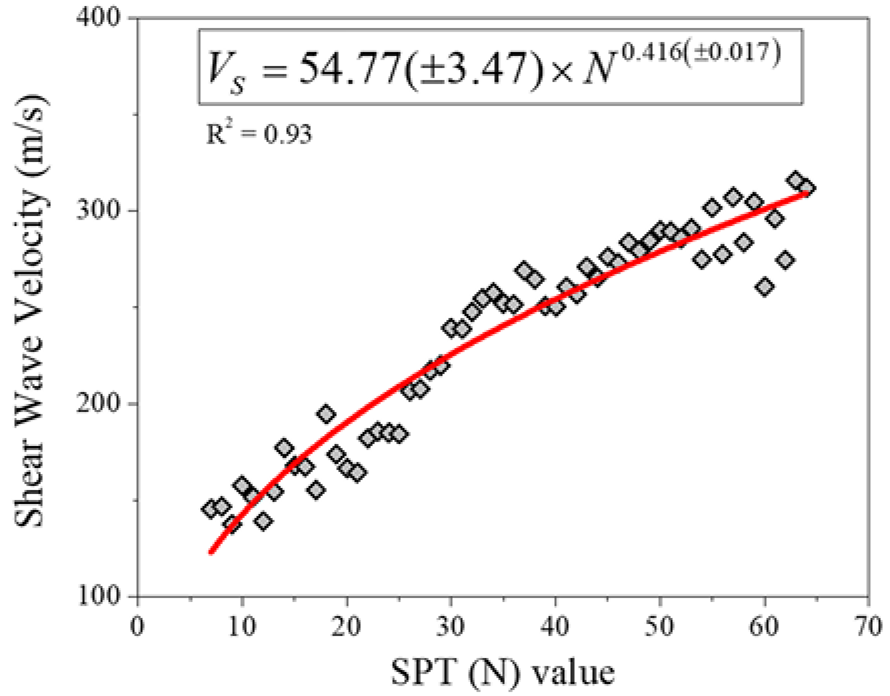


Fig. 16 Developed correlation in the present study between VS and SPT-N for Northern Bihar region. (The solid line represents the fitting curve to the 58 data pairs and diamond shaped symbols represent data points used for training the model)

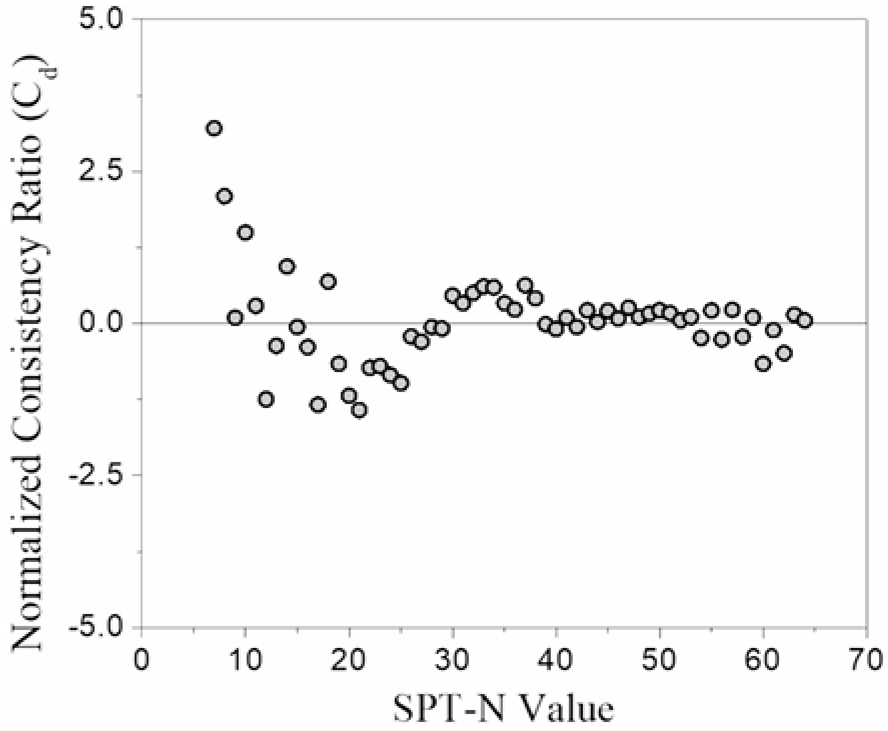


Fig. 17 Normalized consistency ratio (Cd) plot for the current proposed empirical correlation

Site Characterization From Micro Level to Macro Level

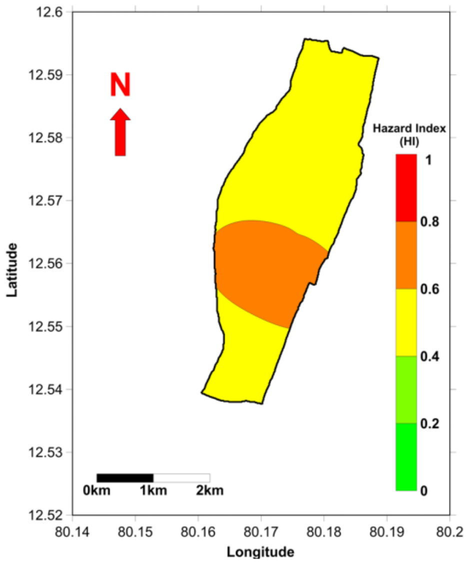
What different levels of Seismic Zonation?

Micro-level	Meso-level	Macro-level
performed small sites hosting critical structures like nuclear power plants (NPP)	performed for the cities and urban centers	performed for a large landmass, such as a state or a country
Earthquake hazard parameters estimated with high degree of reliability	Earthquake hazard parameters estimated with moderate degree of reliability	Earthquake hazard parameters estimated with low degree of reliability

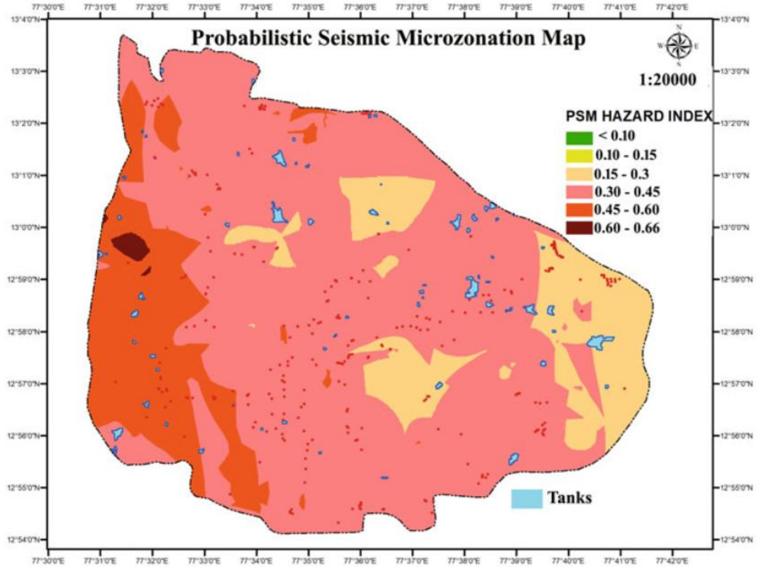
Micro-level

Meso-level

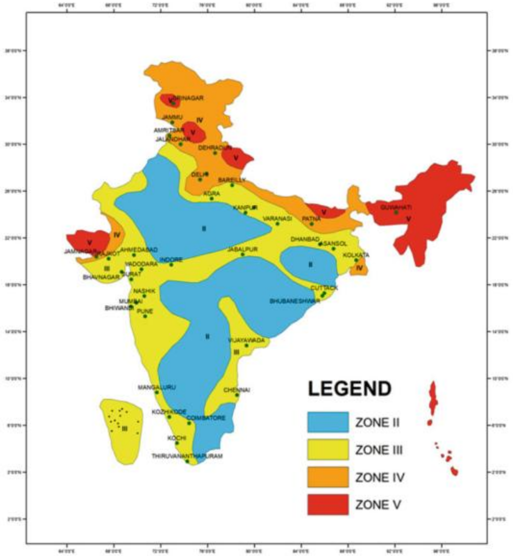
Macro-level



Kalpakkam NPP
After James et. (2014)



Bangalore City
After Sitharam & Anbazhagan (2008)



India
After BIS 1893-(2002)

Feasibility of various methodologies for assessing Site Amplification

- **Empirical Relations**
  - Developed for particular geological unit/site class
  - Is quick and approximate analysis
  - thus less reliable
  - May not incorporate deep basin effects or topographic effects

Suitable for Macro-level study

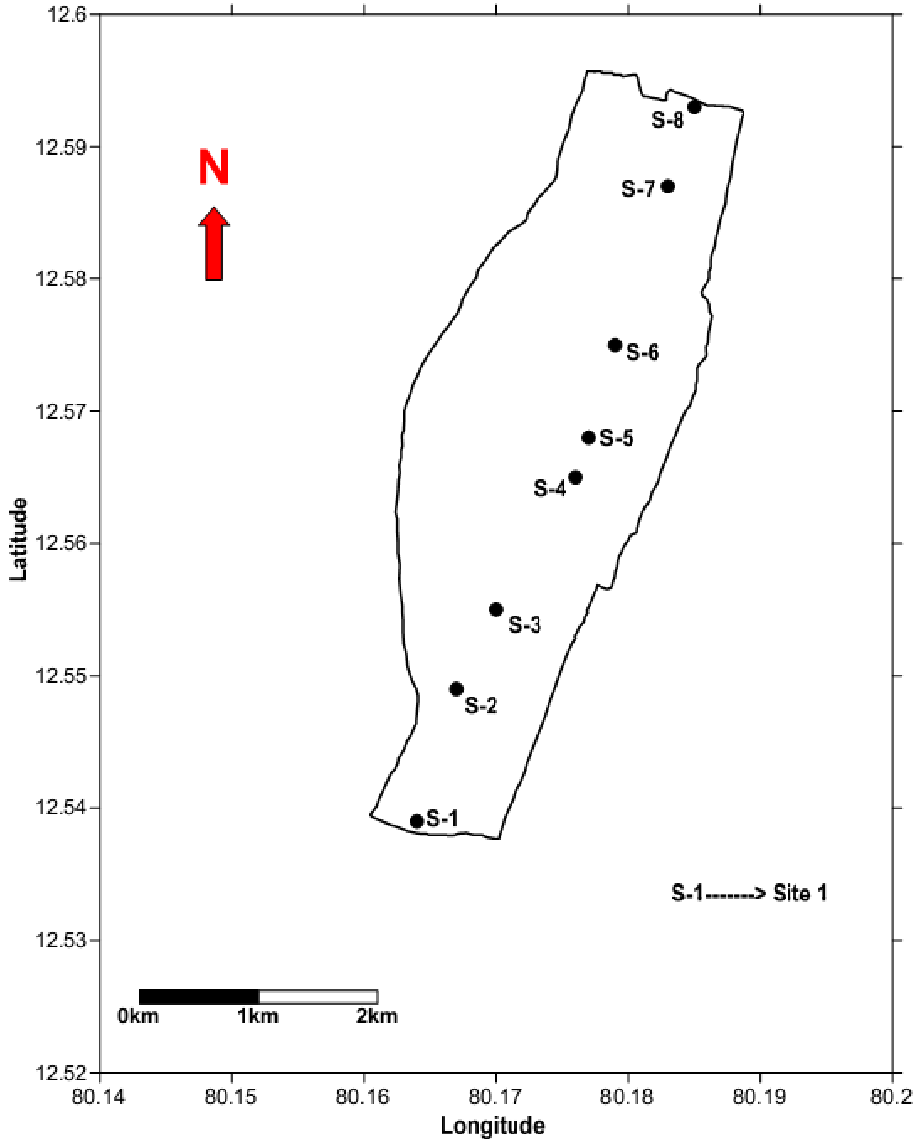
- **Experimental Methods**
  - Based on microtremor/strong motion data
  - Availability of strong motion data both at bedrock and soil??
  - Requires instrumentation
  - H/V microtremor method cannot give a good estimation of the amplification value

Suitable for Meso-level study

- **Numerical Methods**
  - Most accurate and highly reliable
  - Requires geotechnical/geophysical data
  - Requires computation power

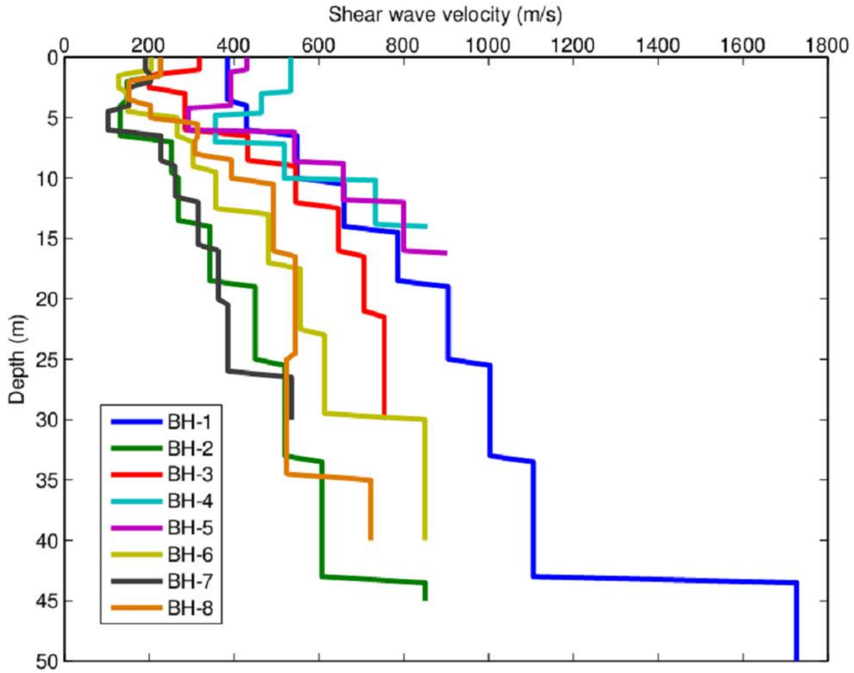
Suitable for Meso to Micro-level study

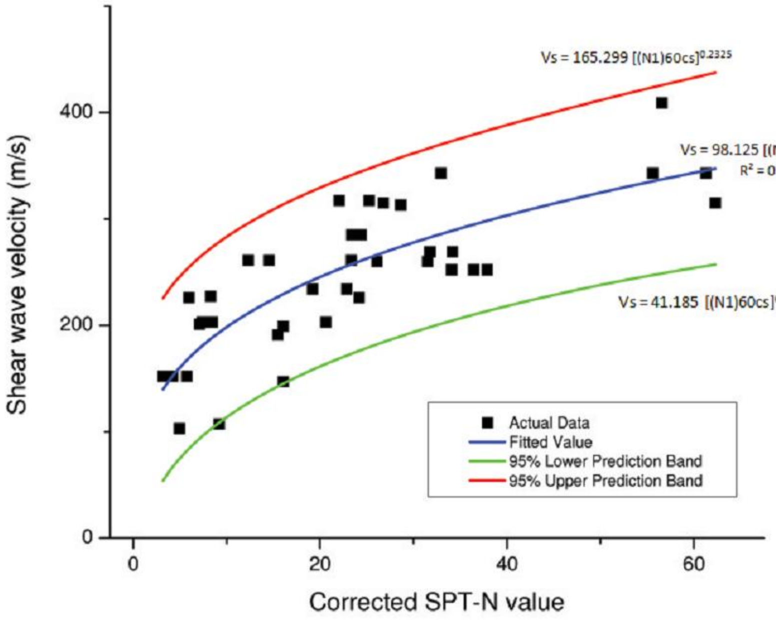
Site Characterization – Micro-level

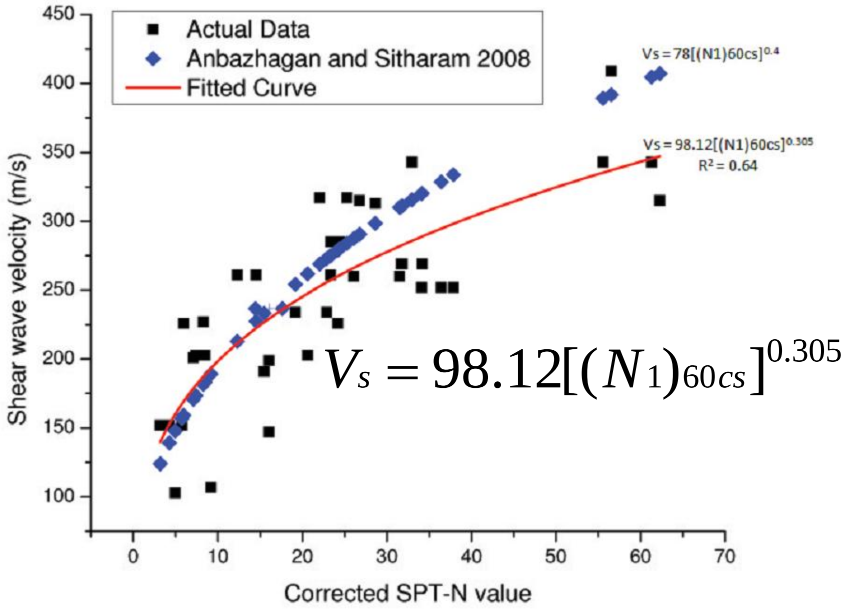


•Multichannel Analysis of Surface Waves (MASW) method is one of the seismic survey

•MASW deduces shear-wave velocity (V_s) variations based on the dispersion pattern of surface waves.

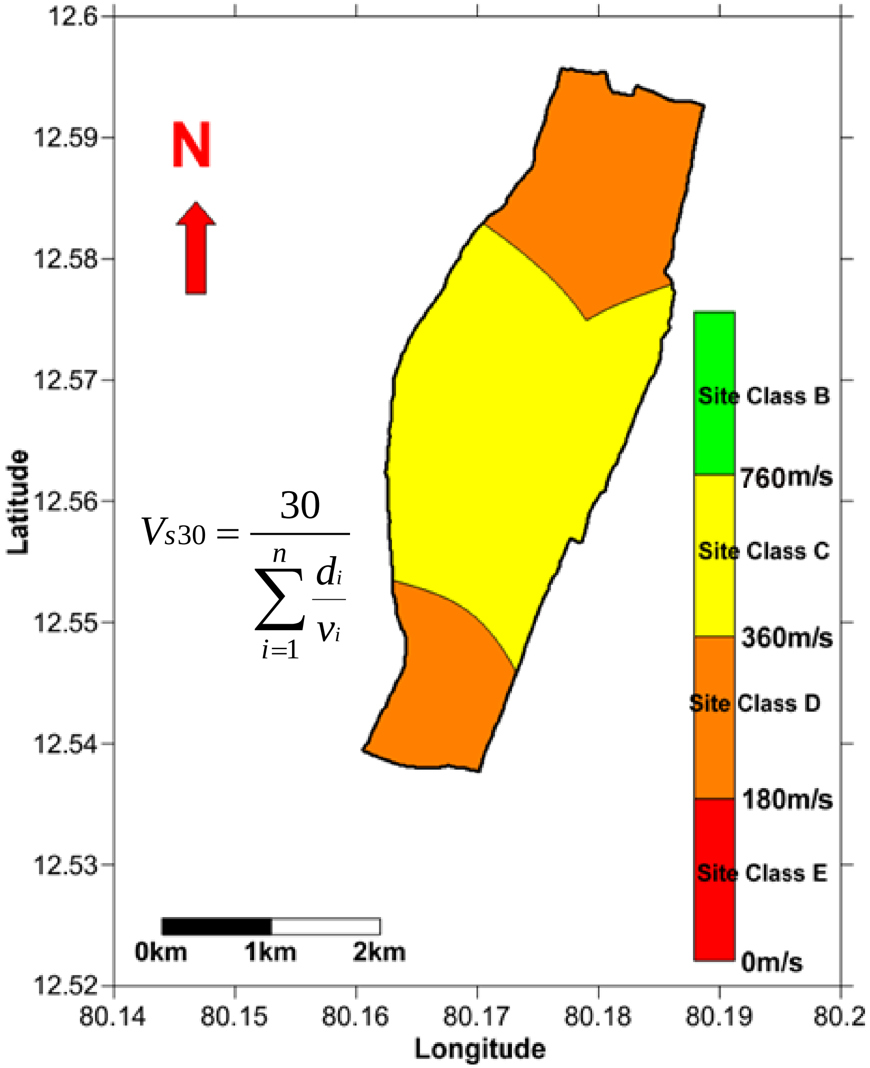






$$V_s = 98.12[(N_1)_{60cs}]^{0.305}$$

James et al. (Under review.) Geotechnical and Geological Engineering (GEGE), (GEGE-S-13-00231)



Site Classification as per NEHRP scheme (BSSC, 2003)

NHERP site class	**Description**	**V_s^{30}**
A	Hard rock	> 1500 m/s
B	Firm and hard rock	760 – 1500 m/s
C	Dense soil, soft rock	360 – 760 m/s
D	Stiff soil	180 – 360 m/s
E	Soft clays, Special study soils, eg. **Liquefiable soil**	< 180 m/s

James et al. "Evaluation Of Dynamic Properties, Local Site Effects And Design Ground Motions For A Nuclear Reactor Site"Geotechnical and Geological Engineering (GEGE), Under review.(GEGE-S-13-00231)

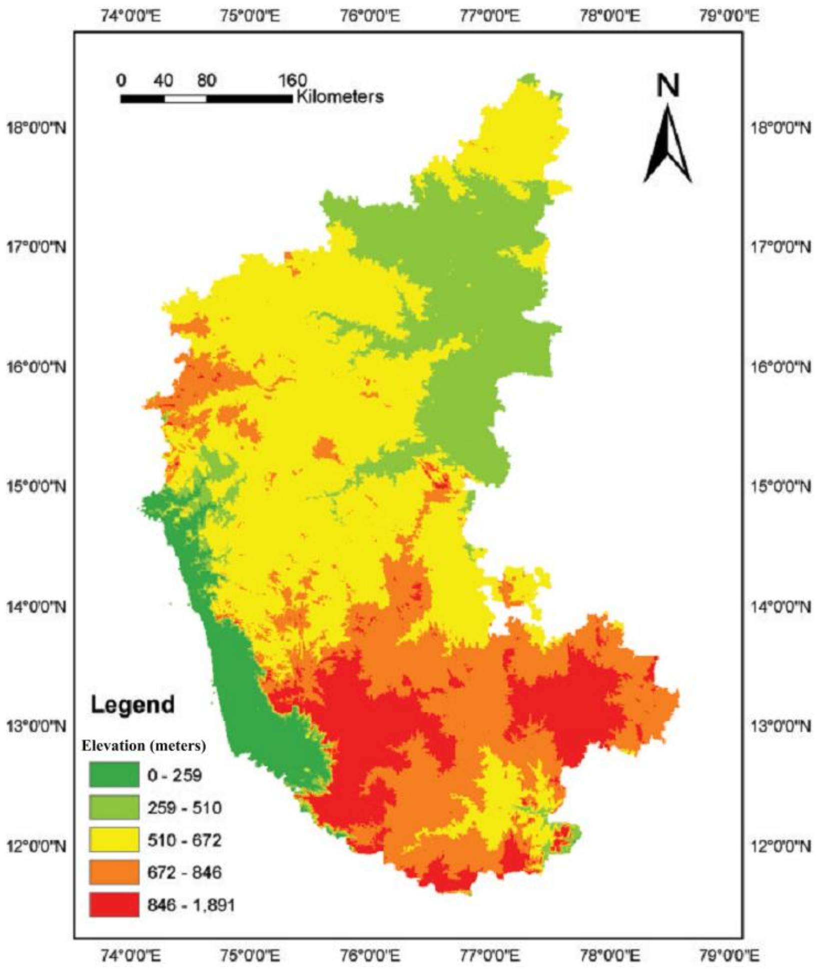
Site Characterization – Macro-level

The topographic variations are an effective index of near-surface geomorphology and lithology (Wald and Allen 2007) .

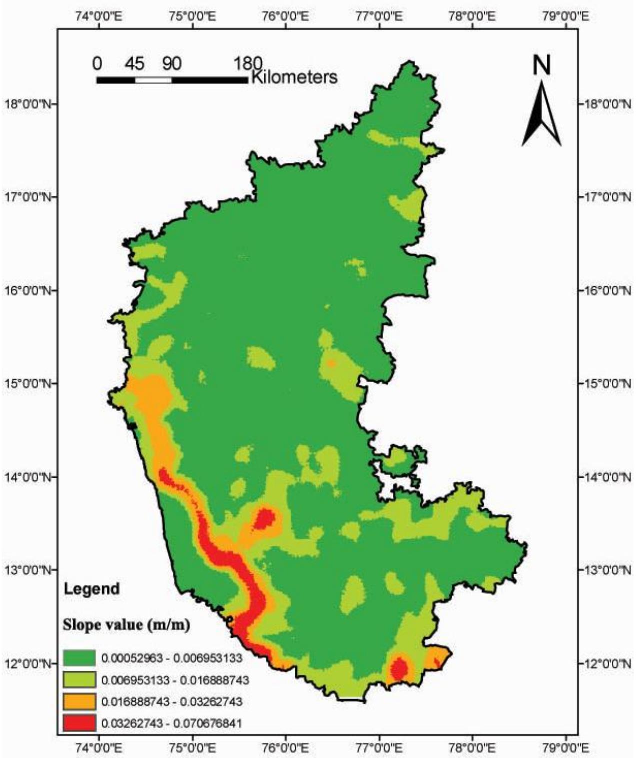
Steep mountains = rocky terrain
Flat basins = soils
Intermediate slope = rock to soil

Macro-level site characterization has been done based on the slope map

The slope maps were derived ASTER GDEM having resolution of 1 arc-second (30 m)



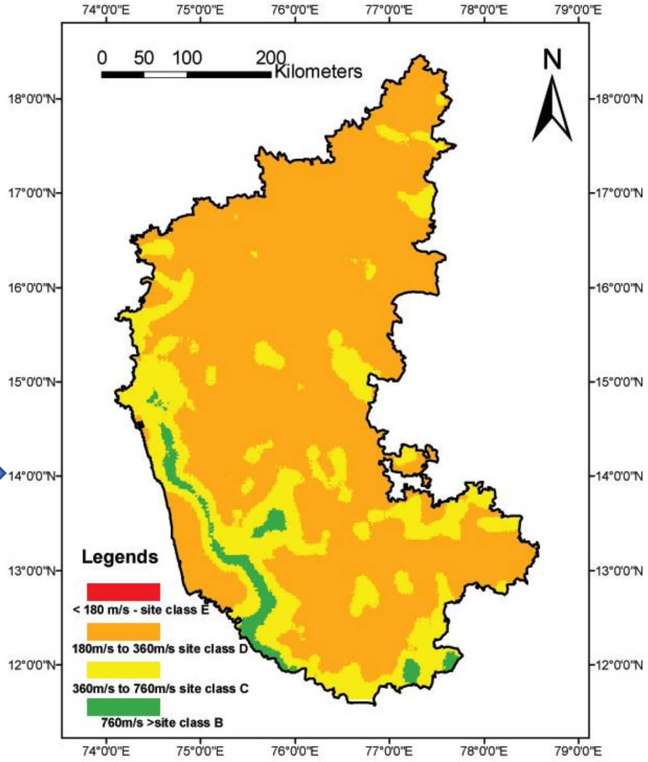
ASTER DEM of Karnataka



grid size = 0.05^0 x 0.05^0 (5km x 5km)

Slope map of the Karnataka state generated using ArcGIS

Spatial distribution of Vs30 values throughout the Karnataka state



Slope ranges for NEHRP Site Classes (Wald and Allen 2007)

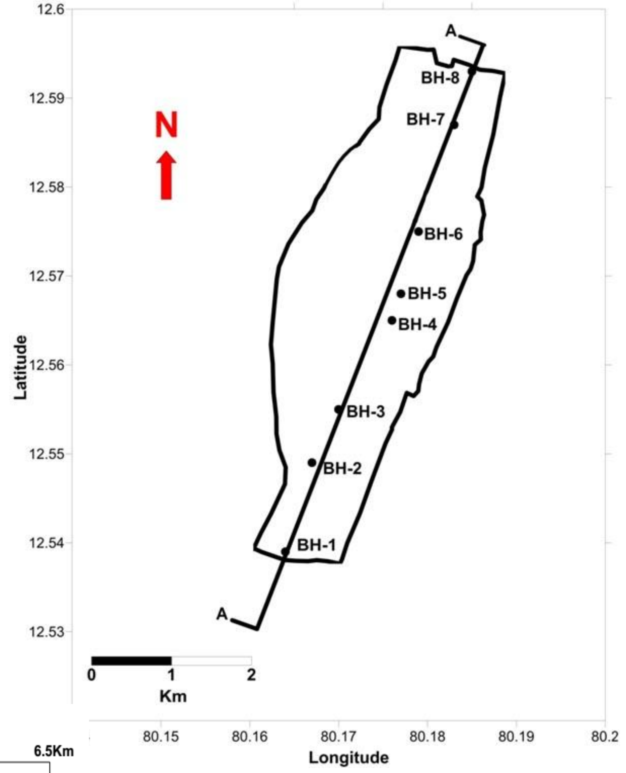
Class	V_{s30} Range (m/Sec)	Slope range *(m/m)*	
		Active tectonic	Stable Continent
E	< 180	<1.0 E-4	<2.0 E-5
D	180-240	1.0E-4 – 2.2E-3	2.0E-5-2.0E-3
	240-300	2.2E-3-6.3E-3	2.0E-3-4.0E-3
	300-360	6.3E-3-0.018	4.0E-3-7.2E-3
C	360-490	0.018-0.050	7.2E-3-0.013
	490-620	0.050-0.10	0.013-0.018
	620-760	0.10-0.138	0.018-0.025
B	>760	>0.138	>0.025

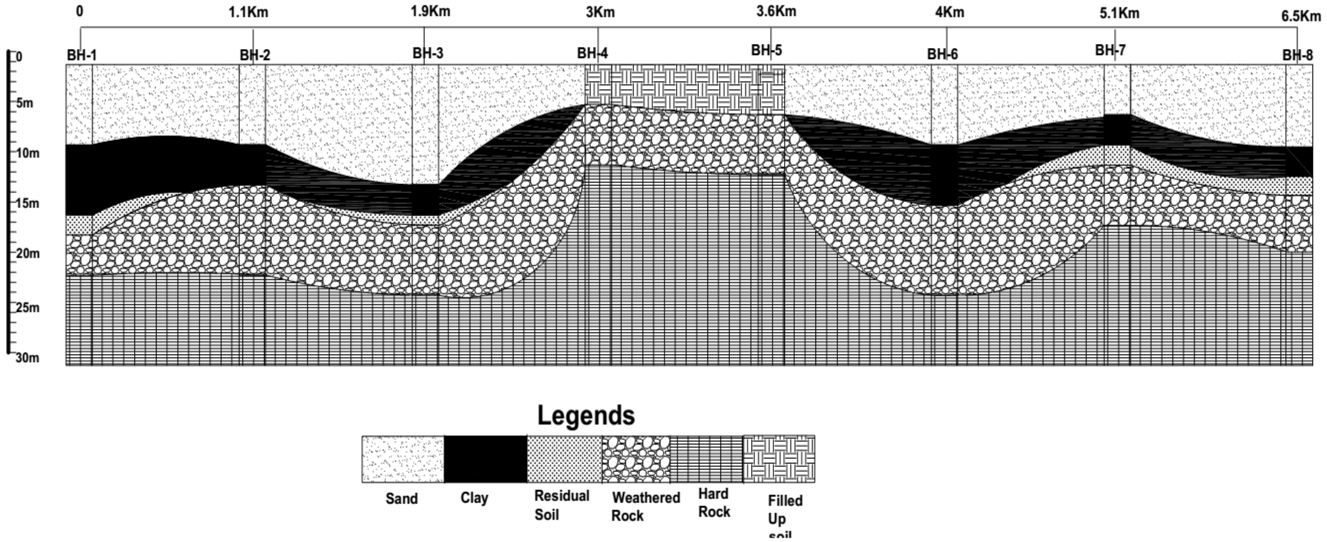
Site Response Studies

Site amplification assessment at Micro-level

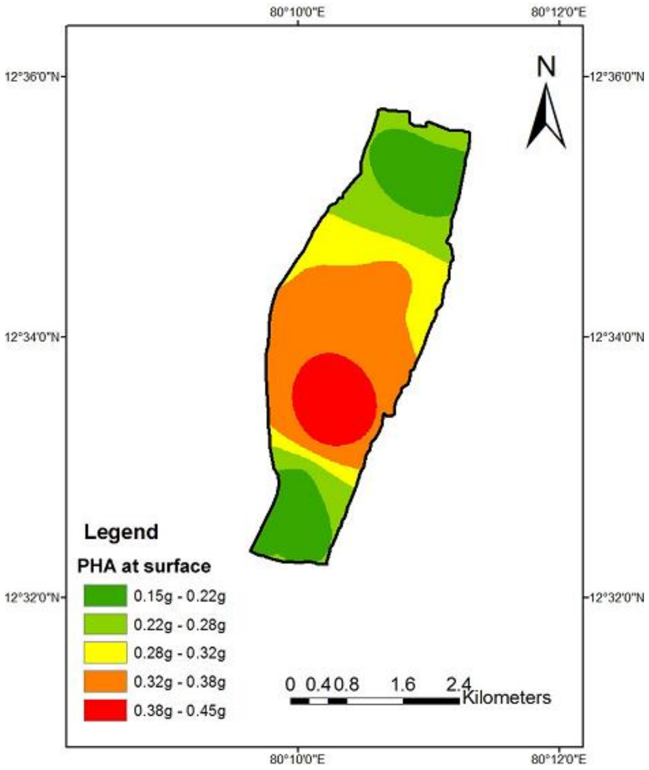
- In the present study, 1D- equivalent linear ground response analysis was carried out to estimate surface ground motion.

- Analysis was done using SHAKE 2000

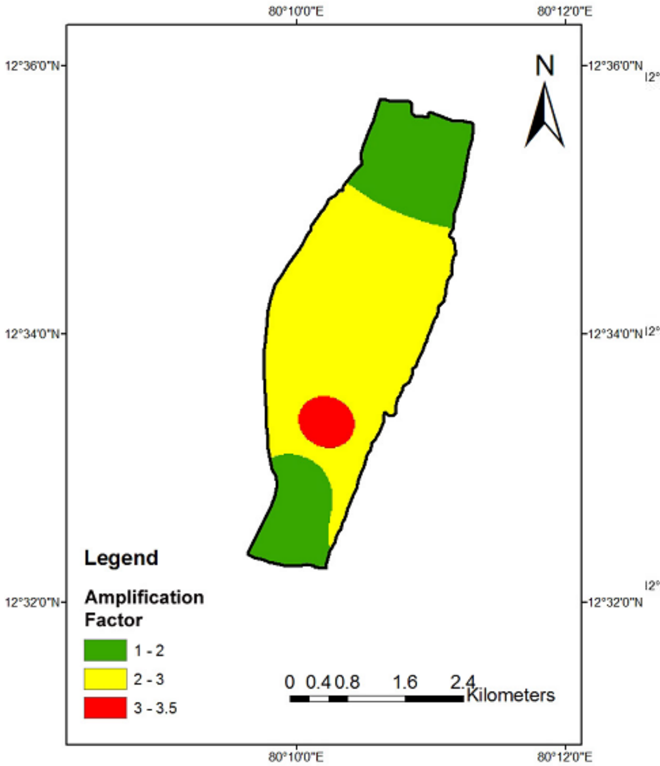




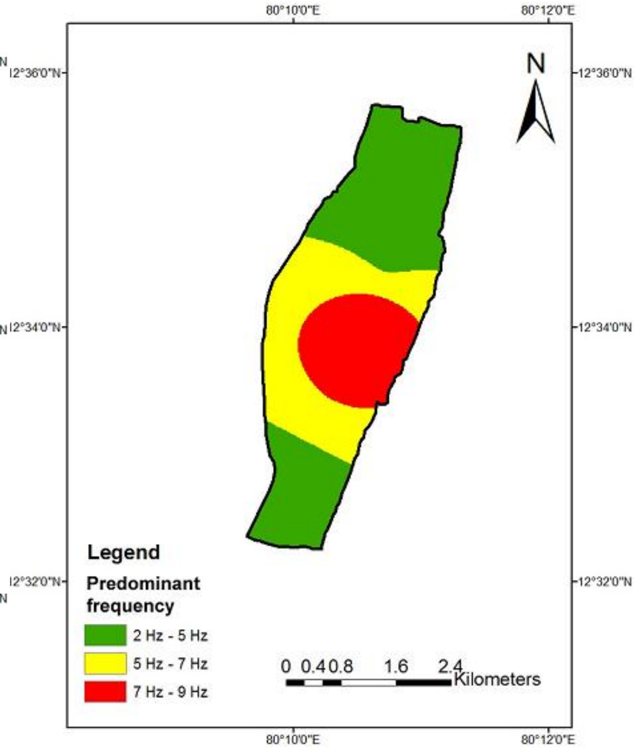
Results Micro-level



Surface level PHA value throughout the NPP site



Amplification factors throughout the NPP site



Predominant frequency throughout the NPP site

Site amplification assessment at Macro-level

- Estimated non-linear site amplification technique proposed by Raghu Kanth & Iyengar (2007)

grid size = 0.05^0 x 0.05^0
(5km x 5km)

- The amplification factor F_s for a given site class estimated.

$$\ln F_s = a_1 y_{br} + a_2 + \ln \delta_s \quad ......(1)$$

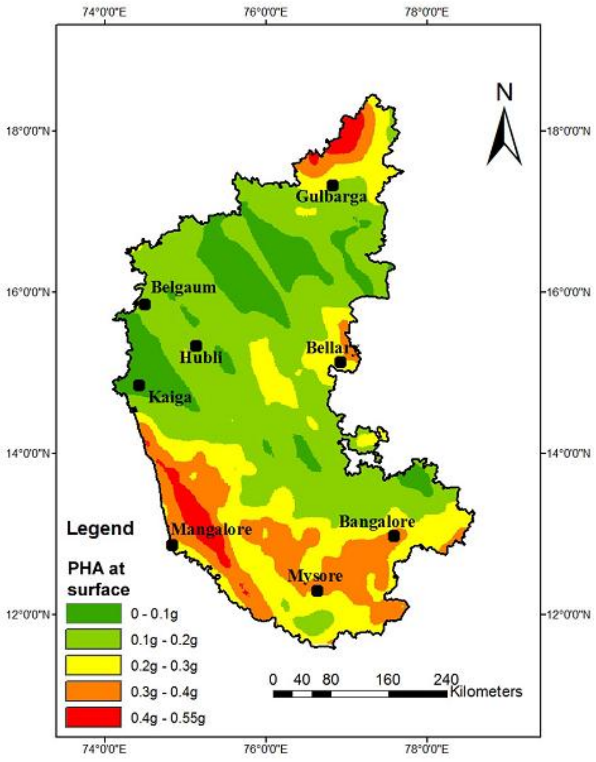
Amplification factor coefficients (after Raghukanth and Iyengar 2007)			
Site class	a_1	a_2	$\ln \delta_s$
A	0.00	0.36	0.03
B	0.00	0.49	0.08
C	-0.89	0.66	0.23
D	-2.61	0.80	0.36

- Acceleration at ground surface y_s is given by

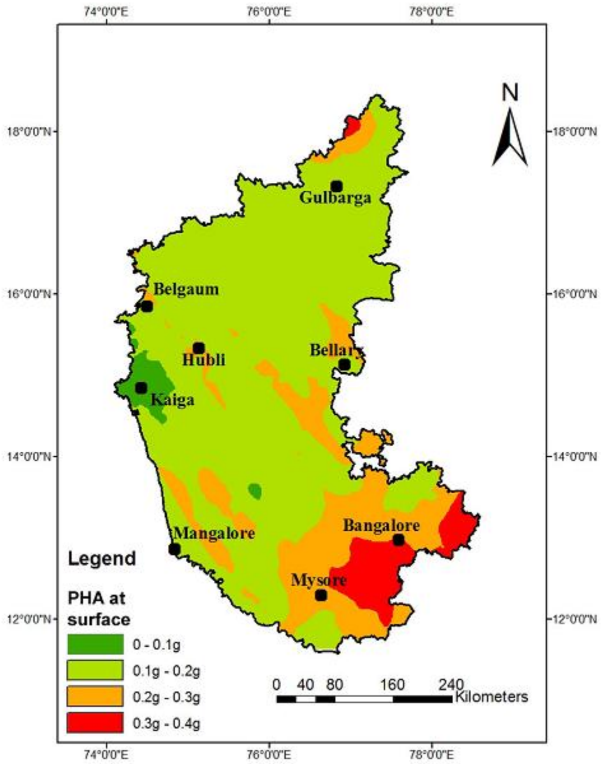
$$y_s = y_{br} \text{ x } F_s \quad ....(2)$$

DSHA and PSHA

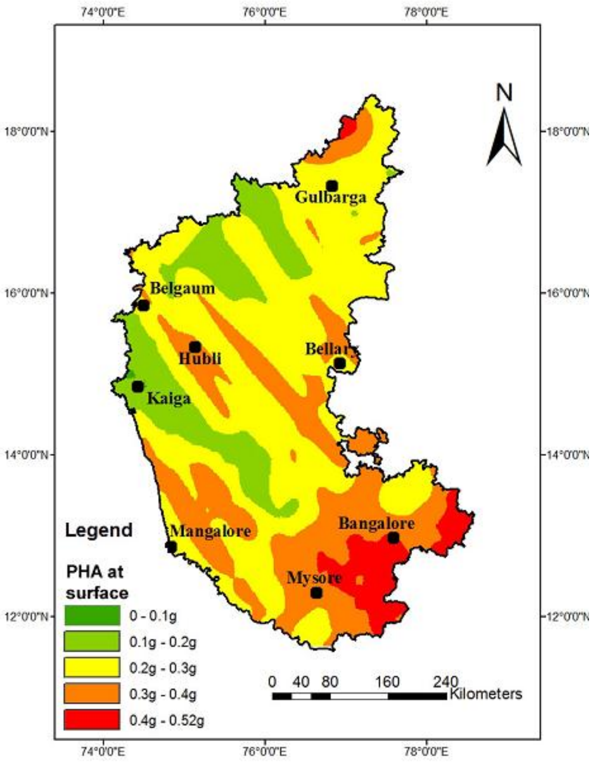
Results Macro-level



DSHA



475 year return period



2500 year return period

Spatial variation of surface level PHA value throughout the Karnataka state

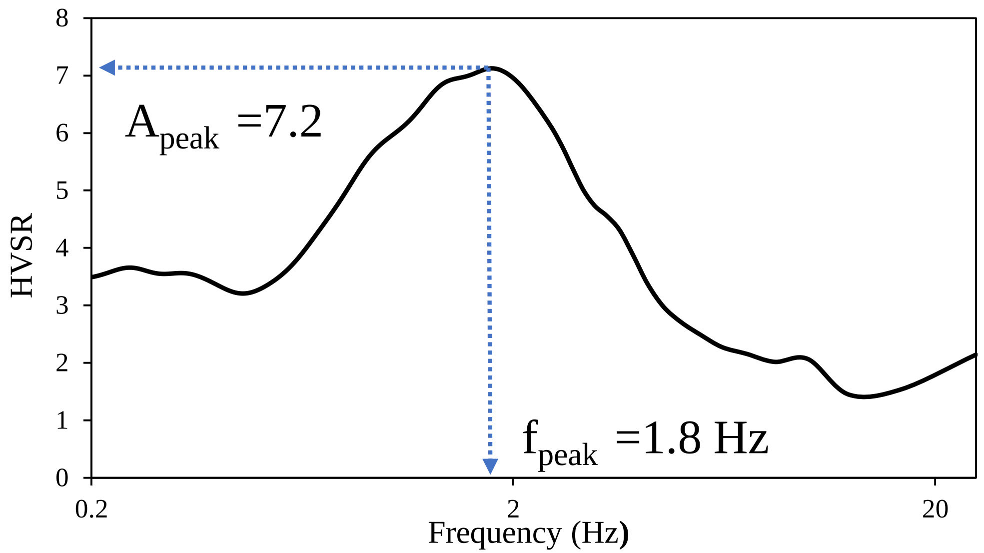
HVSR Calculation

HVSR curve for each recording station is determined using the following steps (Zhao et al. 2005);

1. Calculate the response spectra considering 5% damping, for all the three components (north-south, east-west and vertical) of ground motion records.
2. Smoothen the response spectra of each component using a Konno-Ohmachi (1998) window with a bandwidth parameter "b" of 20.
3. Obtain the geometric mean of the two horizontal response spectra components (H) using equation given below;
4. $H = (H_{EW} \times H_{NS})^{0.5}$
5. Calculate the ratio of H to V (H/V)

6. $(HVSR)_i = \frac{\sum_{i=1}^{Ni} \frac{H}{V}}{N_i}$

N_i is the number of events recorded at recording station "i"



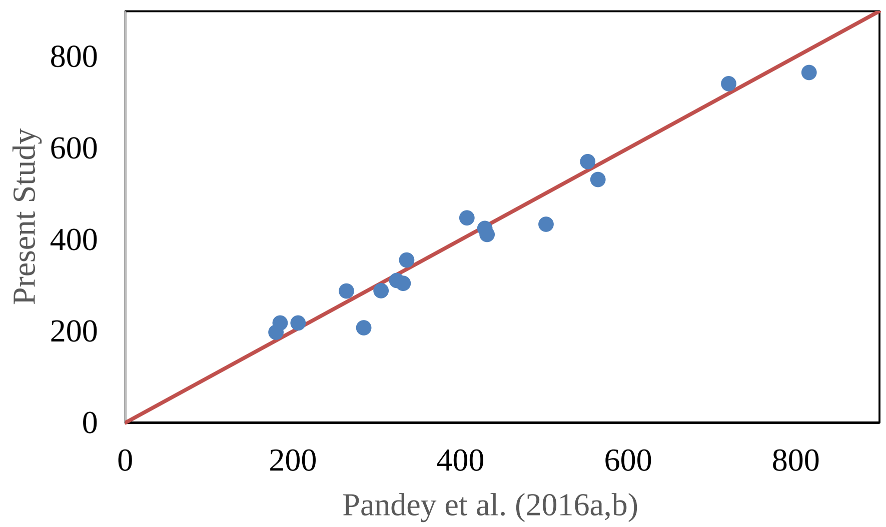
Ref: Harinarayan and Kumar (2017)

Validation of the results of HVSR

In order to compare the value of f_{peak} obtained for recording stations with the shear wave velocity (V_{s30}) reported by Pandey et al. (2016a,b) for the 17 recording stations in Uttarakand and Delhi, the value of f_{peak} is converted to V_{s30} using the following the equation given by Kramer, (1999):

$$V_{s30} = f_{peak} \times 4H$$

Recording Station (1)	V_{S30} from present study (2)	Vs30 from Pandey et al., (2016a,b) (3)	Site Class	
			Given in PESMOS (4)	Actual site class (PESMOS scheme) based on Vs30 obtained from the present study (5)
KHA	206.4	218	C	C
UDM	180	198	C	C
TNK	502.2	434	C	B
KSP	284.55	208	C	C
KOT	407.85	448	B	C
ROO	184.8	218	C	C
RSK	331.5	305	C	C
DUD	305.1	289	A	C
VIK	429	425	C	B
ARI	324	311	C	C
IGN	432	412	C	C
DJB	264	288	B	C
NDI	816	766	A	A
IMD	720	741	B	B
NTPC	336	356	C	C
ANC	552	571	C	C
JAMI	564	532	C	C



Ref: Harinarayan and Kumar (2017)

Earthquakes

Release of building-up energy in the form of seismic waves from inside the earth.

2015 Nepal EQ (M-7.8)

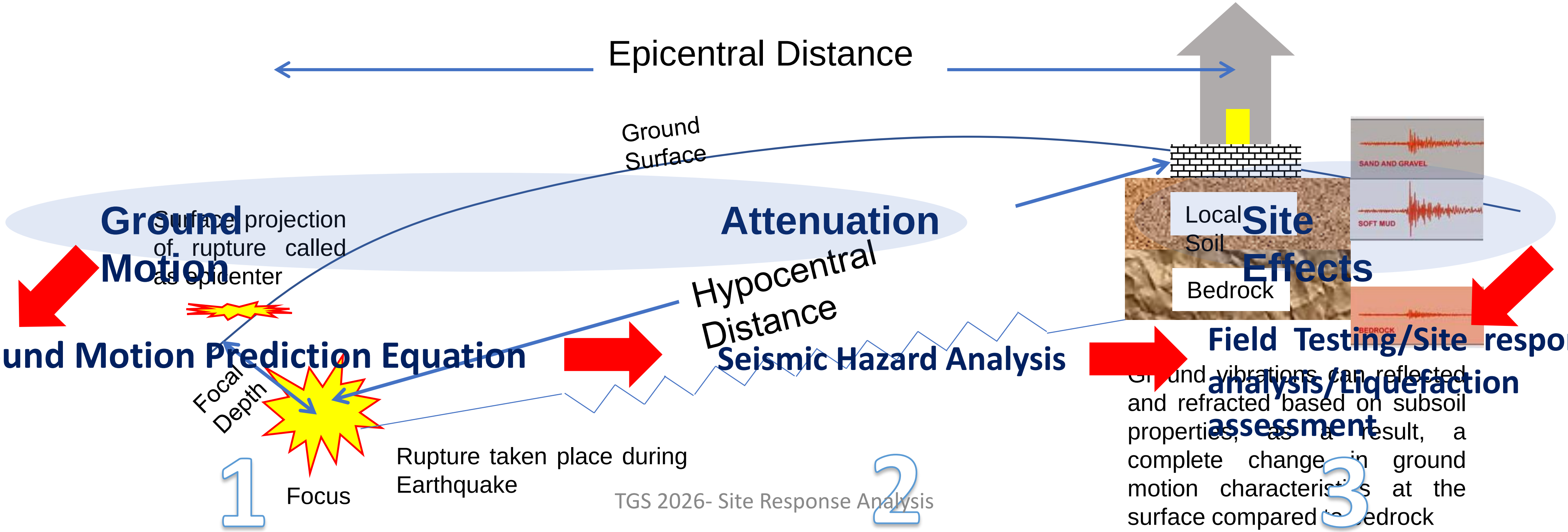
2011 Christchurch EQ (Mw-6.3)

2011 Japan EQ (Mw-9.2)

Source Characteristics

Path Characteristics

Site Characteristics



Ground Motion

Attenuation

Site Effects

Ground Motion Prediction Equation

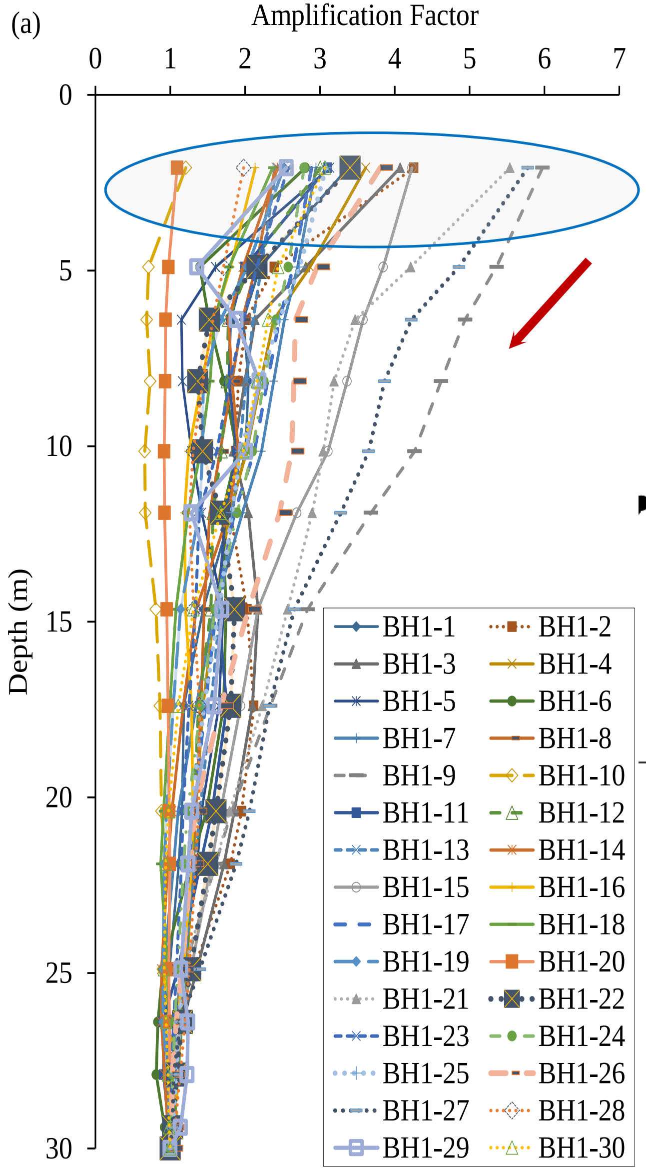
Seismic Hazard Analysis

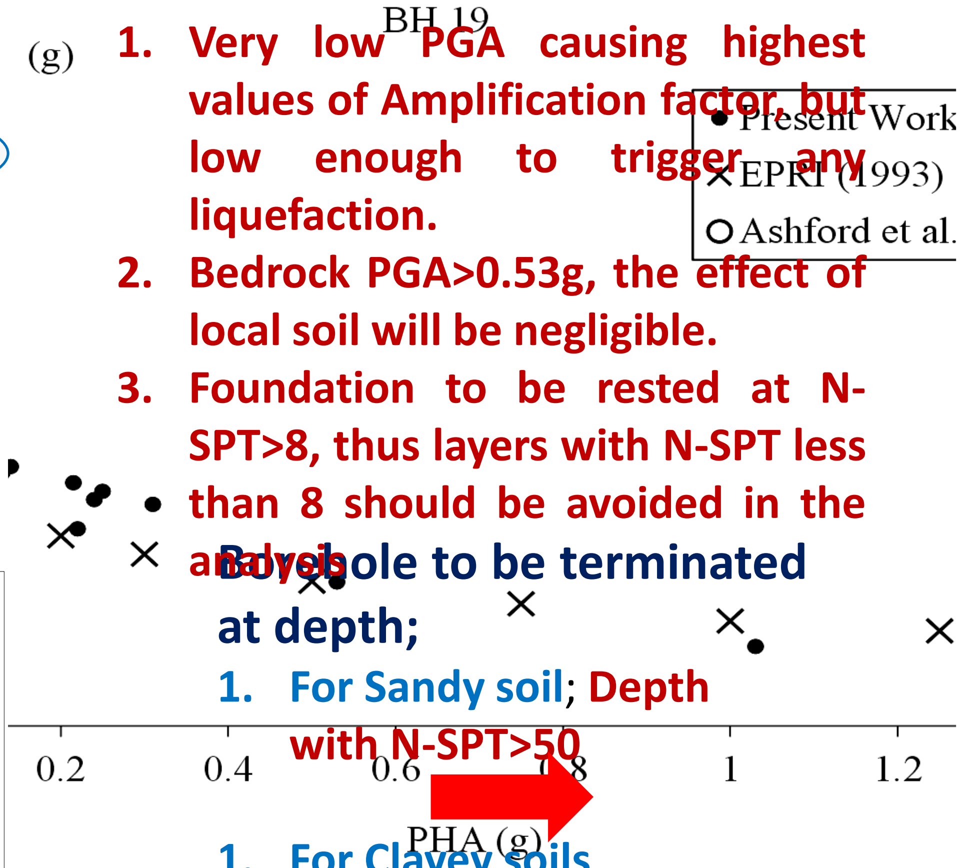
Field Testing/Site response analysis/Liquefaction assessment

Literature

Sr. no.	EQ	M_w	Site effect evidenced	Reference
1.	1985 Michoacan EQ	8.0	**5 times amplification** in bedrock motion in clay deposits in Mexico located at **about 600km epicentral distance**	Finn, (1994)
2.	1989 Loma Prieta EQ	7.0	**2 to 4 times** amplification at soft soil sites in San Francisco bay area located at **120km epicentral distance**	Housner, (1990)
3.	1999 Chamoli EQ	6.5	**Ground shaking** felt up to Nepal, Pune. Considerable damage to buildings in Delhi and Dehradun located at epicentral distance of **200km**	Jain et al., (1999); Mahajan and Virdi (2001)
4.	2001 Bhuj EQ	7.7	Ground failures, liquefaction in **Umedpur** located at **50km** epicentral distance. Considerable ground motion amplification and building damages in **Ahmedabad** located **beyond 350km epicentral distance**	Rajendran et al., (2001), Verma et al., 2014)
5.	2011 Japan EQ	9.0	**Large area undergone liquefaction** and uneven settlement in the city of **Maihama and Tokai Mura** located beyond **150 km epicentral distance**	Nihon, (2011)
6.	2011 Sikkim EQ	6.8	Landslides in areas of Mangan, Jorethang, Lachung, Chungthang etc. located away from the epicentre	Evidenced by PI during field visit post 2011 Sikkim EQ
7.	2015 Nepal EQ	7.8	Sufficient ground shaking in many parts of Northeast India located beyond 400km, several building damages in parts of Bihar, liquefaction in Madhubani	Personnel experience, GSI, 2015

Ref: Kumar et al., (2017)





1. **Very low PGA causing highest values of Amplification factor, but low enough to trigger any liquefaction.**
2. **Bedrock PGA>0.53g, the effect of local soil will be negligible.**
3. **Foundation to be rested at N-SPT>8, thus layers with N-SPT less than 8 should be avoided in the analysis**

Borehole to be terminated at depth;

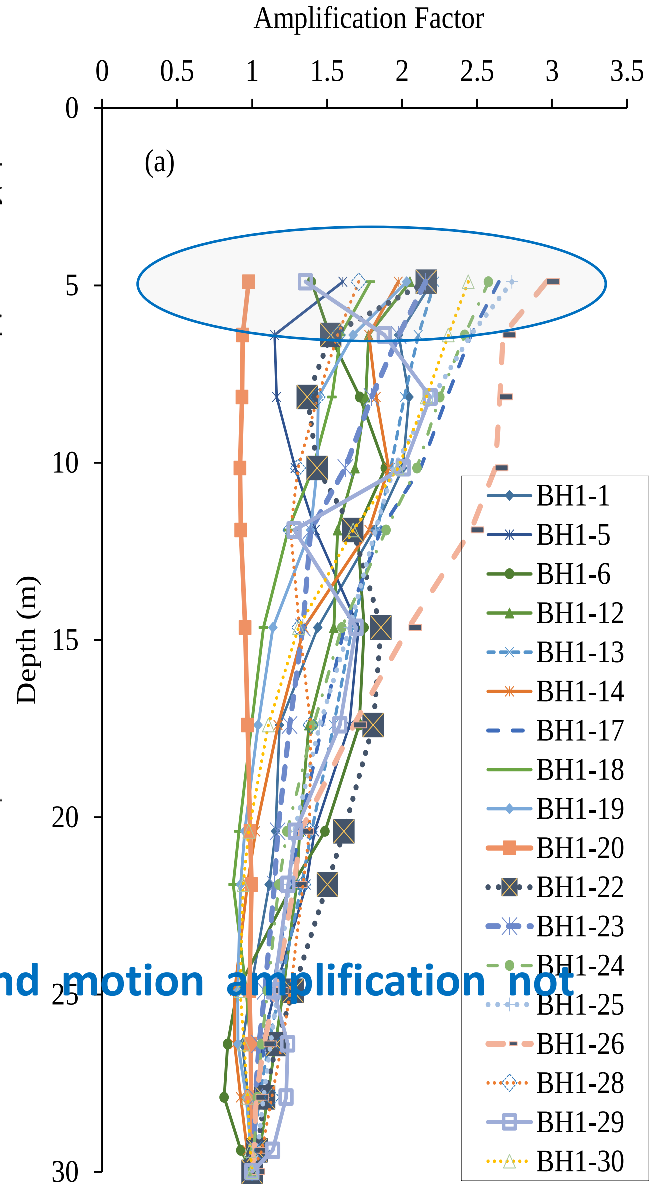
1. **For Sandy soil**; **Depth with N-SPT>50**

1. **For Clayey soils**, **Depth with N-SPT>70**

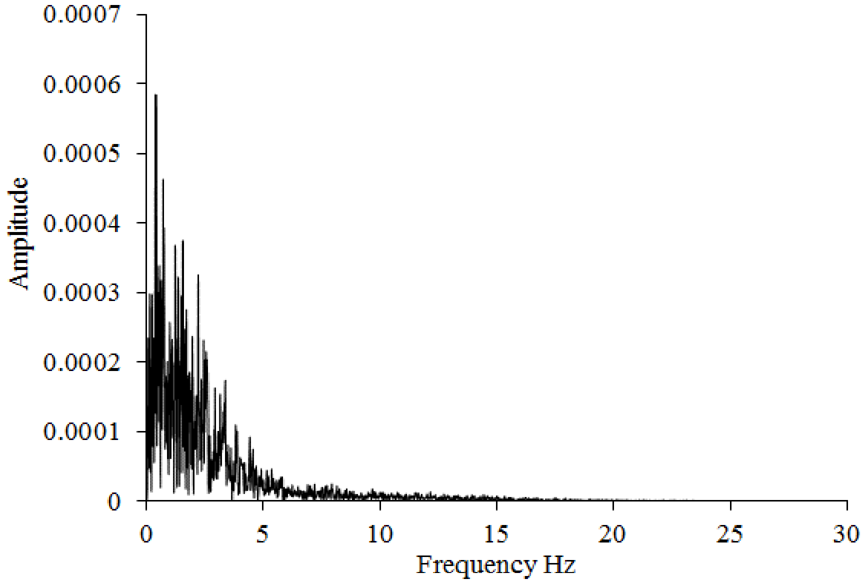
3. **Higher bedrock motion and higher ground motion amplification not possible simultaneously.**

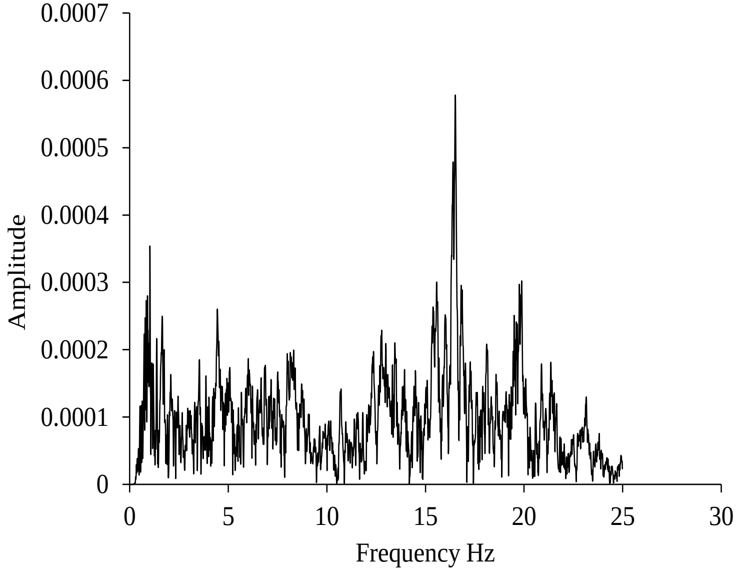
2. **Result in reducing** in design values and thus **the construction cost.**

1. **10-15% decrease** in the borehole drilling cost for shallow deposit regions

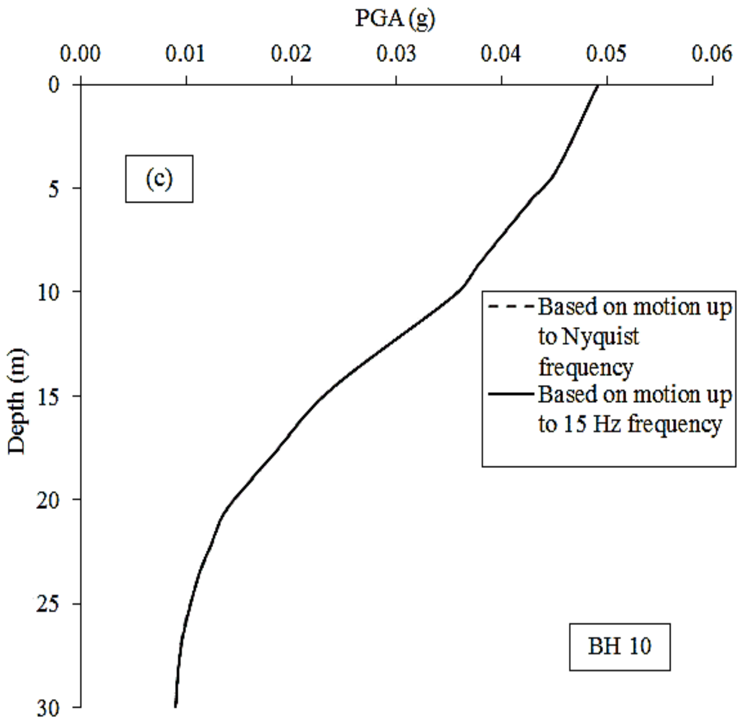


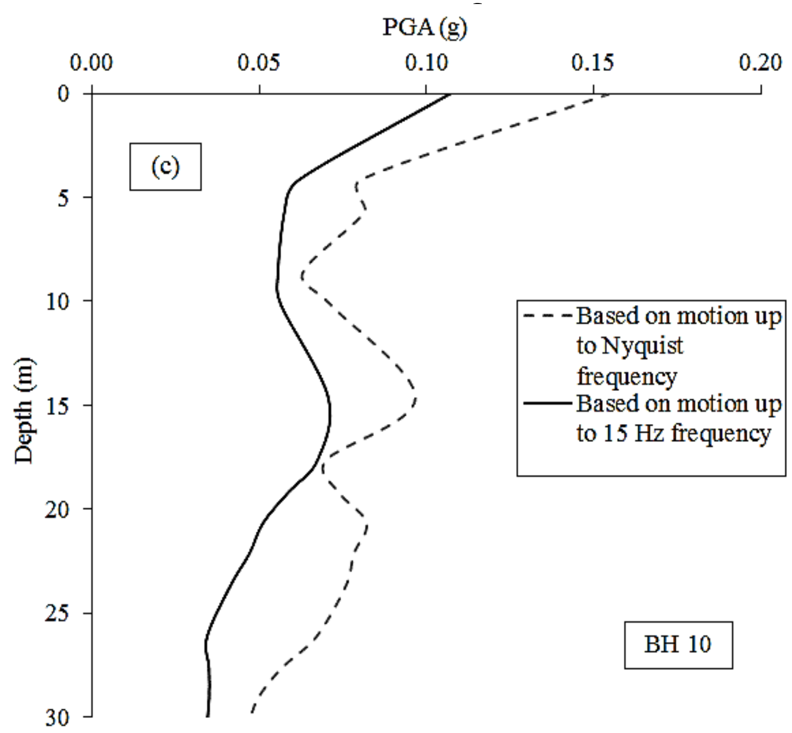
Ref: Kumar et al., (2016)





- ... performing Equivalent ... e
- ... AKE2000 is set as 15 H
- Two ... for Delhi region cosid ... SH ... Nyquist frequency (f_{nyq})





Ref: Mondal and Kumar (2017)

2015 Nepal EQ


Ref: World Vision

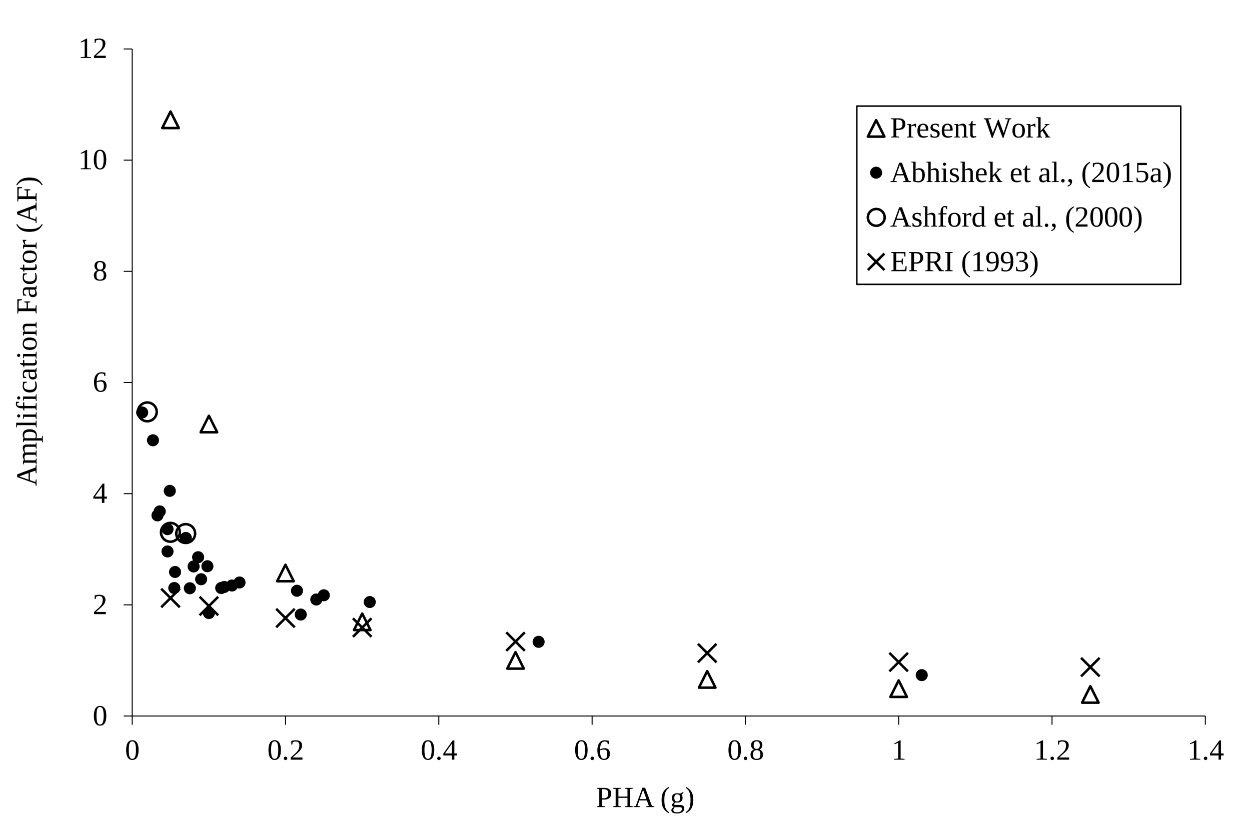
- Date: 25 April, 2015 at 11:56am (NST).
- Mw-7.8.
- Epicentre (Pokhara, NW of Kathmandu, Nepal).
- Focal depth -9km.
- Casualties close to 9000.
- Financial loss-10 billion USD.
- Gap filing event- **Matter of debate.**

Ref: The Huffington post

Was it the first time when so much damages were observed?

Ref: Kumar et al., (2017)

Sr. no.	(EQ)	Magnitude	Damage reported
1	1100	_	Surface displacement of 17m.
2	1255	M-8.1	0.1 million casualties, considerable damages in the Kathmandu valley, almost one-
3			
4			ubsequent cracks and surrounding
5			of Indo-Gangeti
6			ng temples which
7			
8			moderate damage
9			ime span of just illing most of the collapsed in the 3000 houses had
10	1934	M_W-8.4	More than 10,700 fatalities, liquefaction had occurred in the west of Champaran.
11	2015	M_W-7.8	About 9000 fatalities, 22,000 injuries, more than 500,000 destroyed houses, and about 270,000 damaged houses.



1. Role of local soil during 1833 (M-7.7), 1934 (M-8.1) and 2015 (M-7.8) EQ was observed by means of isoseismal maps available.
2. Total 5 locations were

but during different magnitude EQs were observed at 5 different parts of Nepal.

Empirical correlations for response spectra

Period (s)	Correlation
0.0	$SA_0 = SPGA = 0.49\ PHA^{-0.03}$
0.3	$SA_{0.3} = 0.55\ PHA^{-0.02}$
1.0	$SA_{1.0} = 0.58\ PHA^{-0.03}$
3.0	$SA_{3.0} = 0.10\ PHA^{-0.03}$

Note: Based on observed response, the natural period of subsoil was found as 0.3s which was found matching with SCC based one earlier researchers for the selected region.

Ref: Kumar et al., (2017)

Setting Up First Testing equipment: CTx.

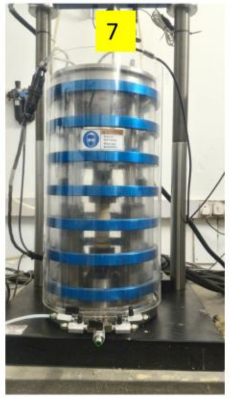
cyclic triaxial setup

The cyclic triaxial apparatus was developed by **M/s Hydraulic & Engineering Instruments Company (HEICO)**, New Delhi under the technical guidance of **Prof. T.G. Sitharam** with the financial support from **Department of Science and Technology (DST) (Seismology division), Govt. of India,**

The facility is been used for following research works

- Study the behavior of soils subjected to dynamic loading (both stress and strain controlled
- To understand the liquefaction behavior
- To estimate the dynamic soil properties such as shear modulus (G) and damping (D) required for design of geotechnical structures subjected to earthquake loading.

Setting Up First Testing equipment: CTx.



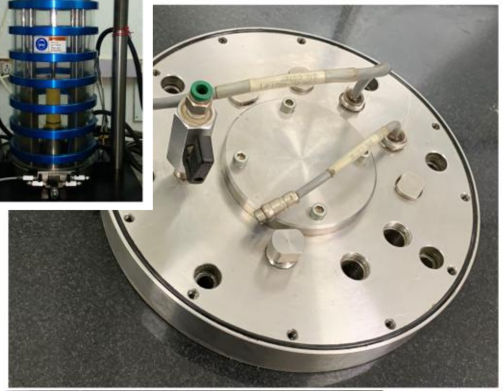
1. PCP-200: Pressure Control Panel 2. Fiber optics sensor signal conditioner 3. Resonant column (RC) motor amplifier	4. SCON-2000 System controller 5. Motor with calibration specimen 6. Computer	7. Soil specimen enclosed with cell wall for RC test 8. CTx. test specimen

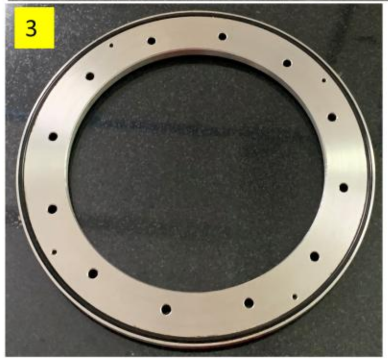
Torsional/Resonant column cum cyclic triaxial setup

- ✓ **Funded by BARC -DAE**
- ✓ **Individually maintained & also testing others samples**
- ✓ **Developing Shear Modulus & Damping Model of Indian Soil**

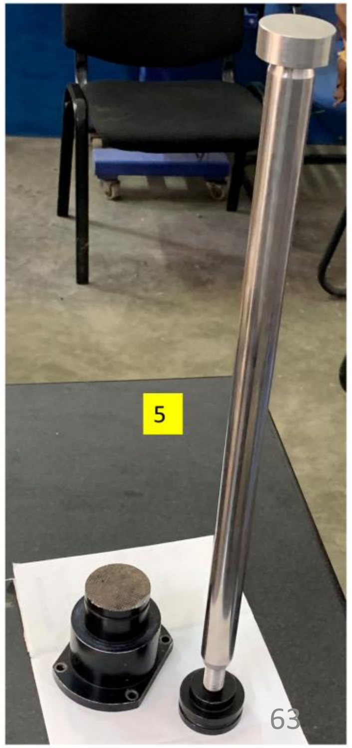
- ✓ **120 Lakhs**
- ✓ **Size sample tests 38, 50 &100 mm diameter samples**
- ✓ **Measures G & D from 10^{-05} to 10 % strain continuously**

Unique Equipment components

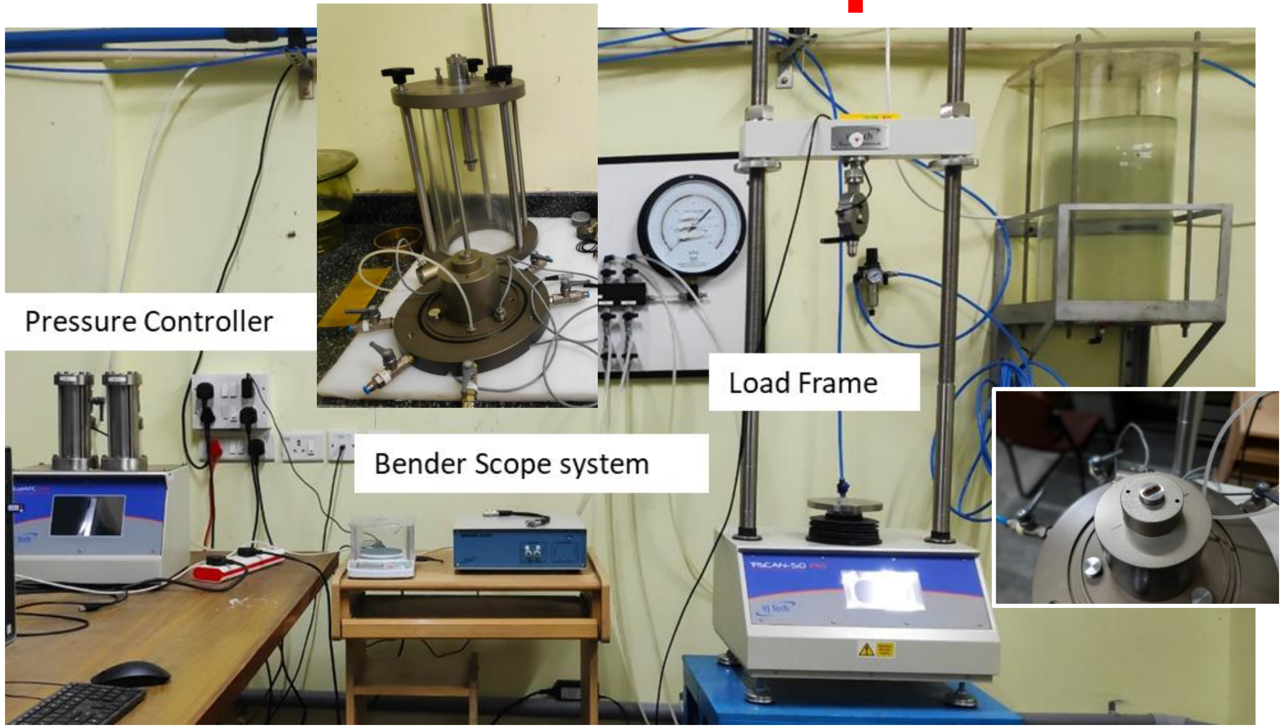


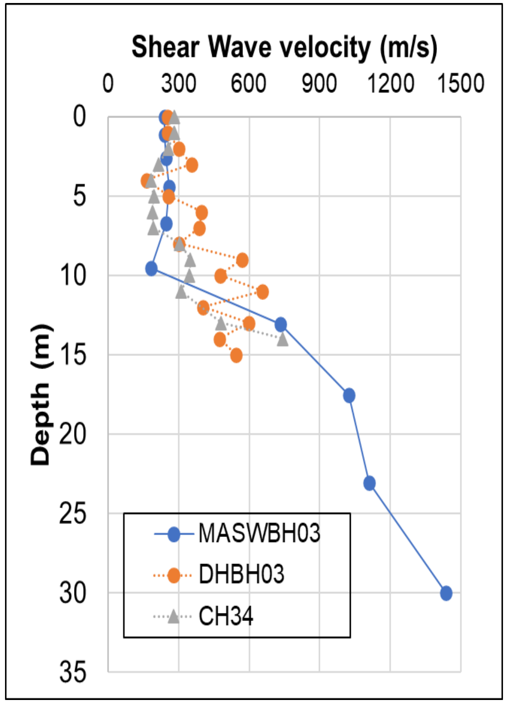


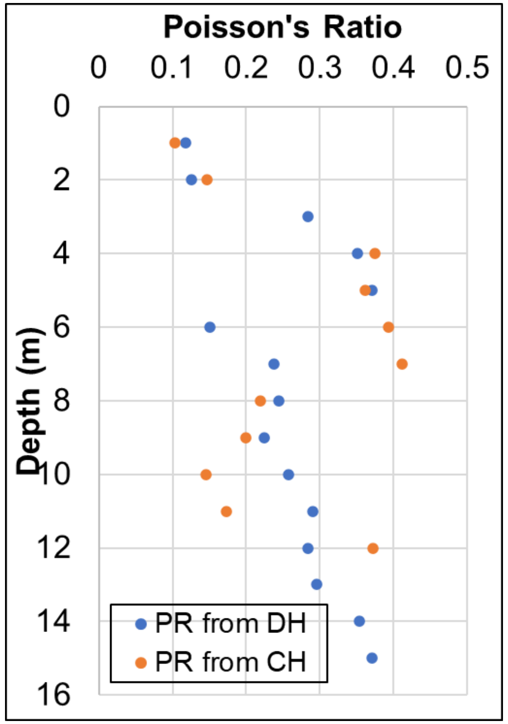
1. Cell top for resonant column test
2. Cell top for cyclic triaxial test
3. Ring to be placed on the cell tops
4. Base pedestal and specimen top cap
5. Loading shaft or piston connected to the specimen top cap



Field & Lab Comparison – Dynamic Properties

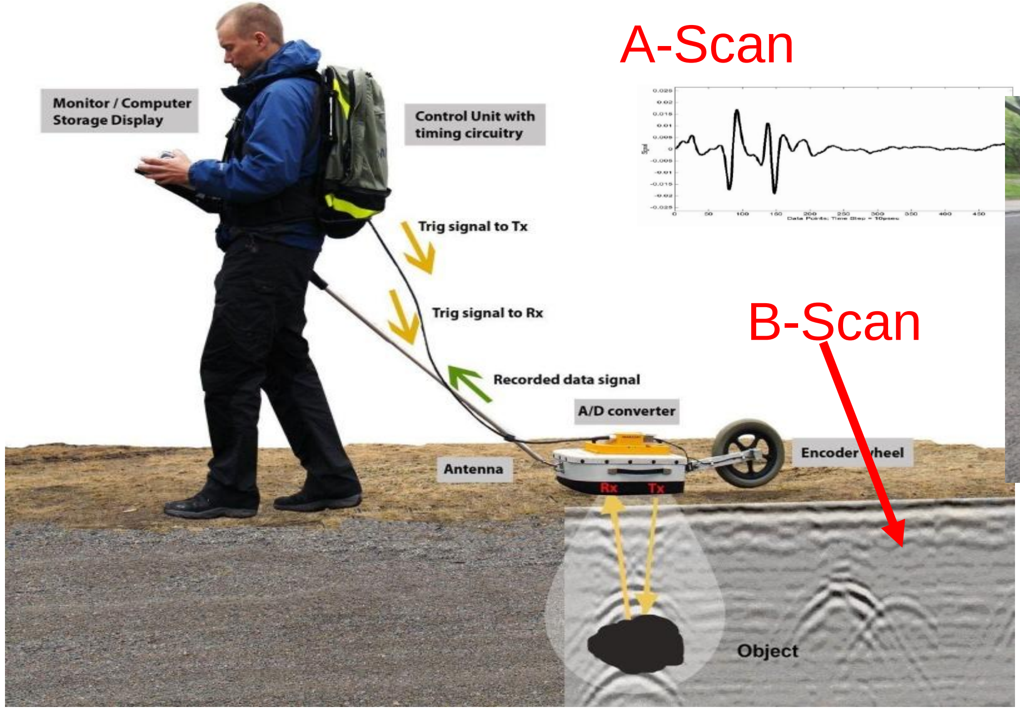


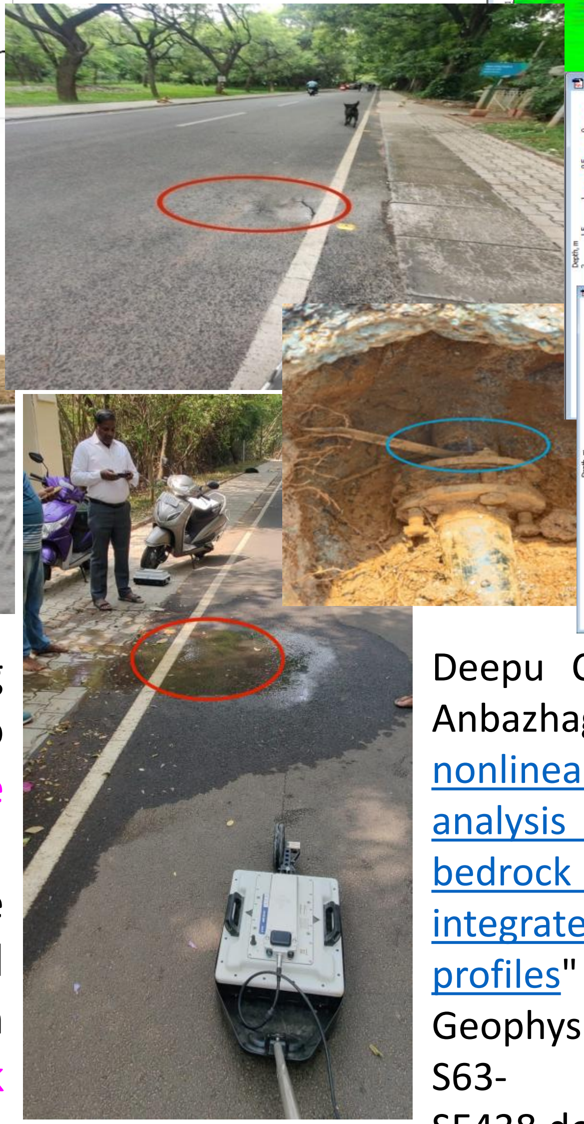


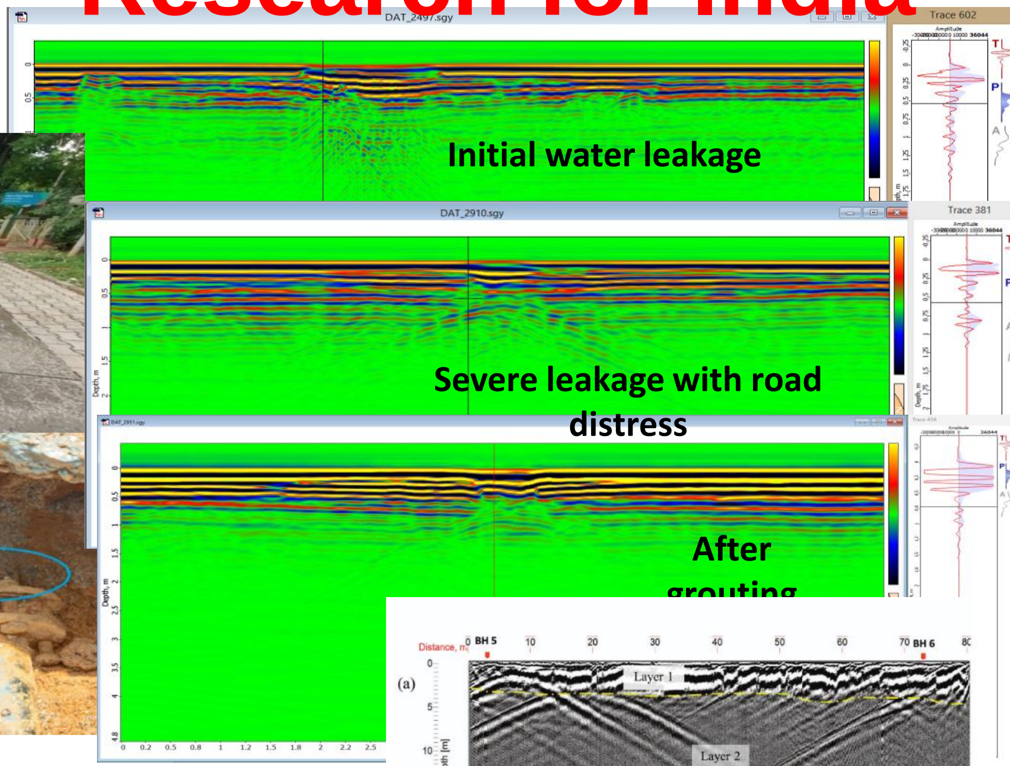


- ❖ Study effect of failure state and respective P& W waves and Poisson's Ratio
- ❖ Compare of field and lab results, model extreme saturation due Urban flooding
- ❖ Understanding variation of SBC & settlement of Bangalore soil, which causing more settlement and instability during heavy rain - BBMP identifies over 500 dilapidated structures in preliminary report - https://www.thehindu.com/news/cities/bangalore/bbmp-identifies-over-500-dilapidated-structures-in-preliminary-report/article37083189.ece
- ❖ Model Poisson ratio for different degree saturation and stress conditions

Site Characterization using GPR – Research for India

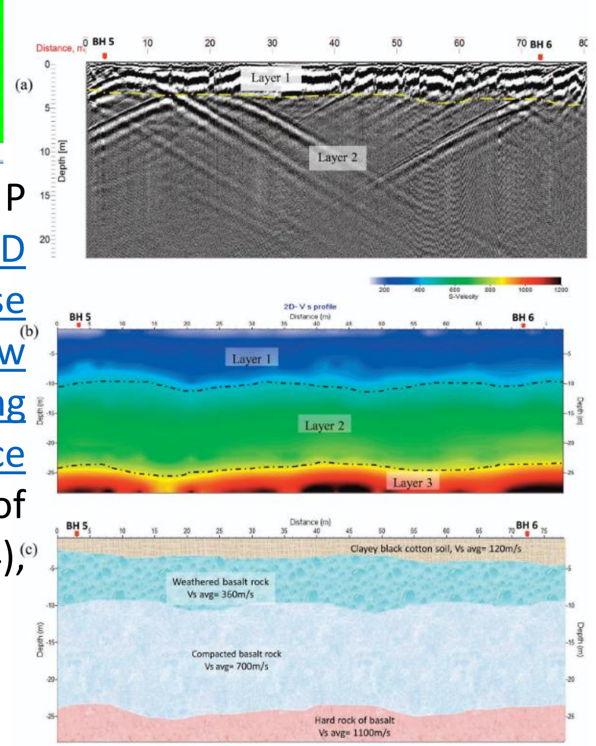






- ✓ Non – destructive test that utilizes propagating electromagnetic (EM) waves that respond to changes in the electromagnetic properties of the shallow subsurface.
- ✓ Physical properties important to GPR include *Dielectric Permittivity*, *Electrical Conductivity,* and *Magnetic Permeability*, that is a dependent on soil and rock material, water content, and bulk density.

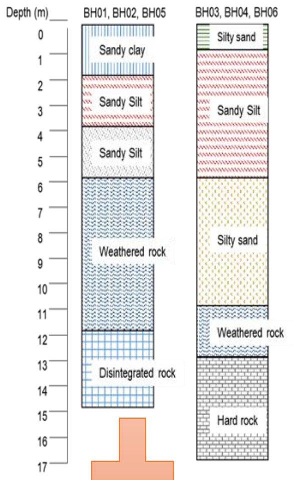
Deepu Chandran, and P Anbazhagan (2020). "[2D nonlinear site response analysis of shallow bedrock sites using integrated subsurface profiles]" Annals of Geophysics. Vol 63(4), S63-SE438,doi:10.4401/ag-8326

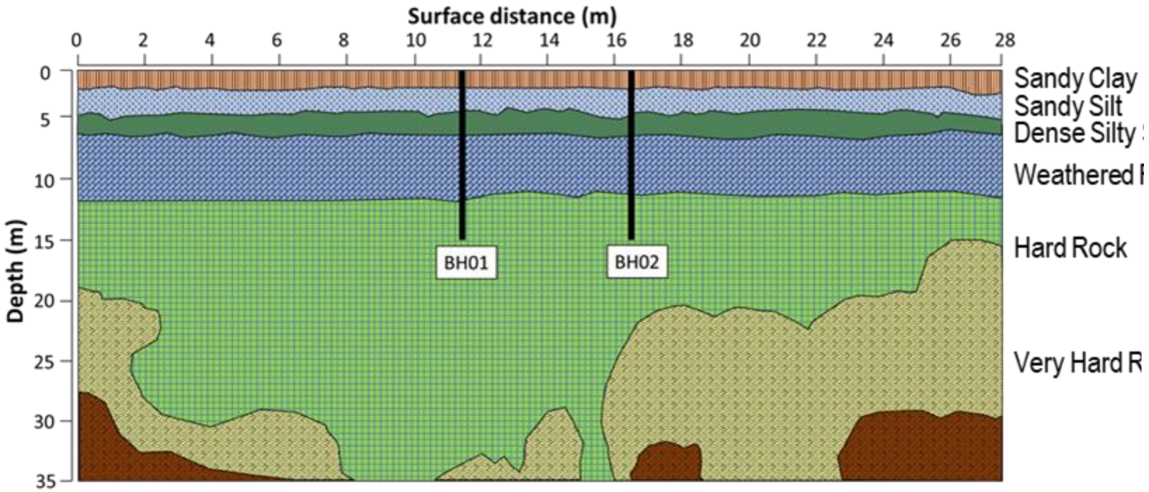


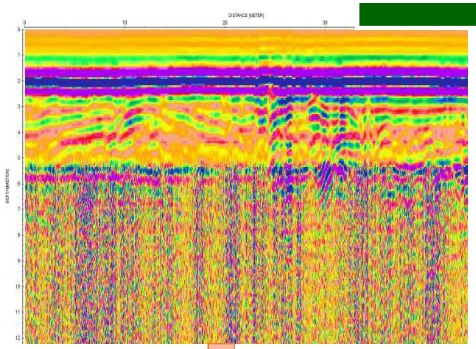
SPT N Correlations with Vs or Gmax

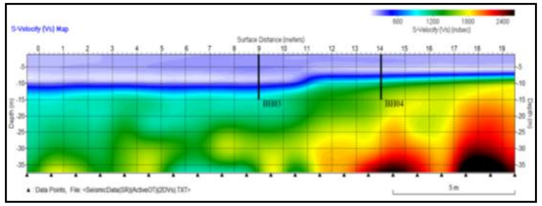
- SPT N is the most widely is measured in-situ property in India and predominately used to obtain Vs or Gmax.
- $G_{max} or\ V_s = aN^b$
- Several such correlations were developed in India after 2005, before people use correlations developed in other countries
- SPT N values are affected by several parameters and need to apply correction to account these error

Integrated Subsurface Profile





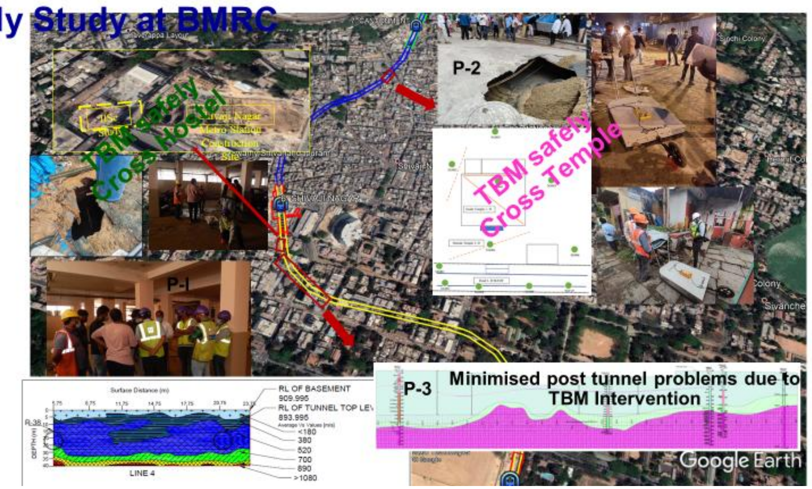


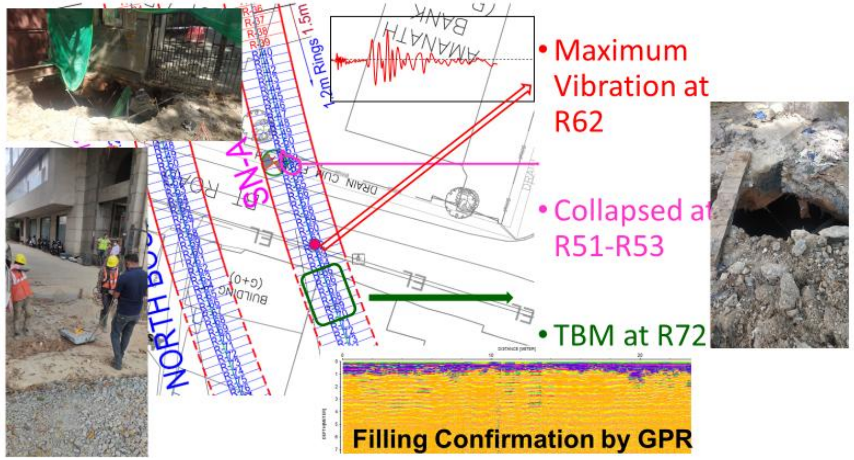


Layer	ρ (g/cc)	Vs (m/s)	G (MPa)	Poisson's ratio	E (MPa)	K (MPa)
Sandy Clay	1.75	200-280	70-137	0.3	182-356	152-297
Sandy Silt	1.80	200-350	72-221	0.4	202-619	337-1032
Dense Silty Sand	1.75	190-320	63-179	0.42	179-508	373-1058
Weathered Rock	2.1	400-700	336-1029	0.32	887-2717	821-2516
Hard Rock	2.3	700-1500	1127-5175	0.3	2930-13455	2442-11213
Very Hard Rock	2.6	1500-2000	5850-10400	0.3	15210-27040	12675-22533

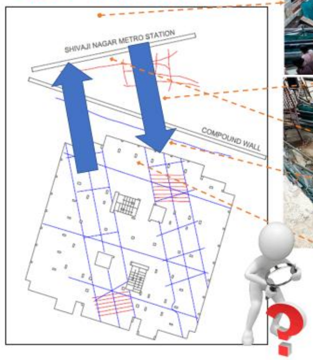
Cavity Formation

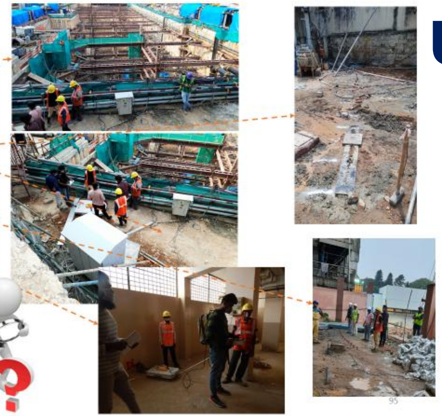
My Study at BMRC





Site Condition





Used by

Airport
Metro Rail
Nuclear Power Plants
Dams

Dynamic soil properties based on IGRA

Laboratory investigations

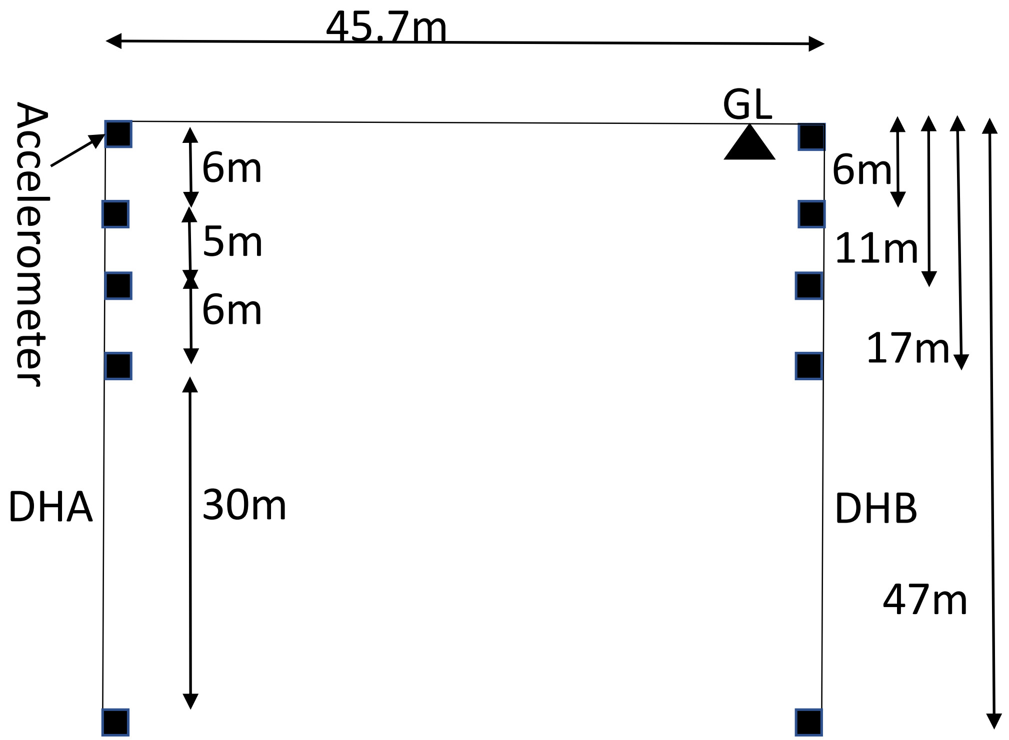
ADVANTAGES

- Stress history, stress path, τ-γ levels can be controlled during testing.

DISADVANTAGES

- ***Sample disturbance***
- ***Testing procedure:*** time of consolidation, consolidation increment, size and rate of back pressuring, cell fluid, measurement devices, strain rate, method of calculations
- ***Equipment compliance:*** membrane compliance, inappropriate coupling between sample and loading boundary, machine compliance and friction (EPRI/NSF, 1991)
- ***Testing technique***
- ***Macro (ground) vs micro (sample)***

Vertical seismic arrays



Ref: Mondal and Kumar (2021)

Results for Single layer

Table 1, Back calculated dynamic soil properties for surficial layer at DHB

Motion no.	γ_{eff} (%)	V_s (m/s)	β (%)	p	% Error in PGA
1	0.092	68.237	13.600	0.052	-0.29
2	0.003	121.605	2.658	0.074	5.30
3	0.060	76.589	10.251	0.118	-11.61
4	0.082	61.580	8.000	0.097	9.46
5	0.006	112.469	0.193	0.307	-7.73
6	0.005	107.323	5.163	0.070	7.79
7	0.003	123.267	2.810	0.900	0.26
8	0.003	121.880	4.000	0.463	5.67
9	0.009	104.039	10.500	0.054	-9.01
10	0.012	105.482	8.300	0.052	-4.68
11	0.037	83.967	17.800	0.050	0.22
12	0.006	123.213	0.924	0.134	-7.28
13	0.007	117.893	4.211	0.147	-12.76
14	0.015	99.908	10.950	0.051	-6.80
15	0.014	101.969	4.979	0.693	-4.70

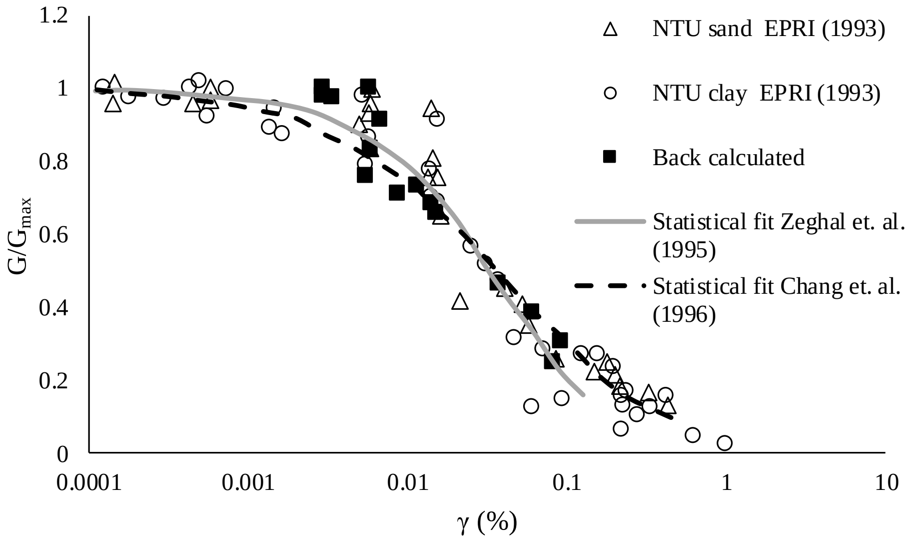


Figure 4: back computed G/G_{max} values

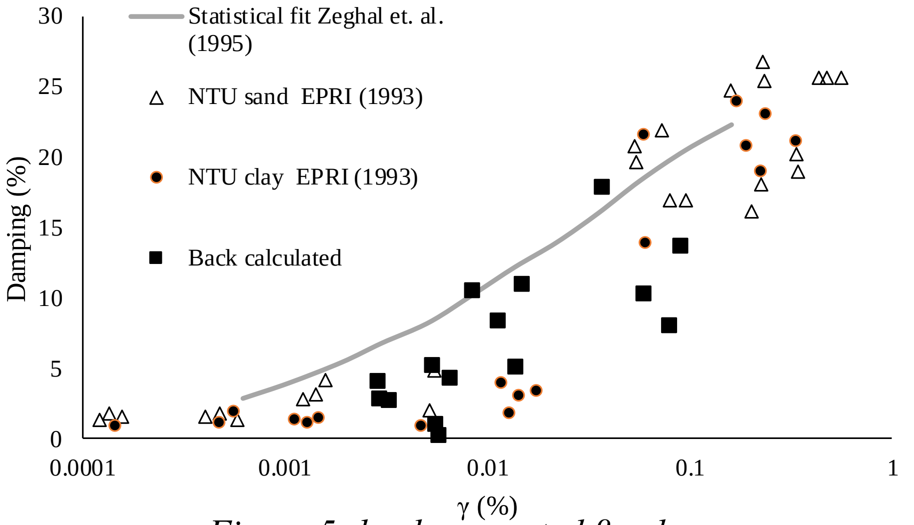


Figure 5: back computed β values

Ref: Mondal and Kumar (2021)

Results for Two layer system

Table 2, Back calculated dynamic soil properties for surficial layer at IWTH27

Motion no.	γ_{eff}(%)	V_s(m/s)	β(%)	G/G_{max}	p	% Error (in PGA value)
Motion 1	0.0039	128.53	0.5	0.73	0.65	9.86
Motion 2	0.0048	150.00	2	1.00	0.34	-9.59
Motion 3	0.0177	134.43	6.6	0.80	0.06	-24.06
Motion 4	0.0324	130.68	3.7	0.76	0.73	-9.96
Motion 5	0.1299	80.08	8.2	0.29	0.05	-23.51
Motion 6	0.0089	130.57	3.6	0.76	0.38	-9.39
Motion 7	0.1669	71.65	6	0.23	0.05	-6.40
Motion 8	0.0064	150.00	2	1.00	0.89	1.97
Motion 9	0.0205	137.71	10	0.84	0.05	-15.29
Motion 10	0.0154	132.93	6.2	0.79	0.84	-9.73

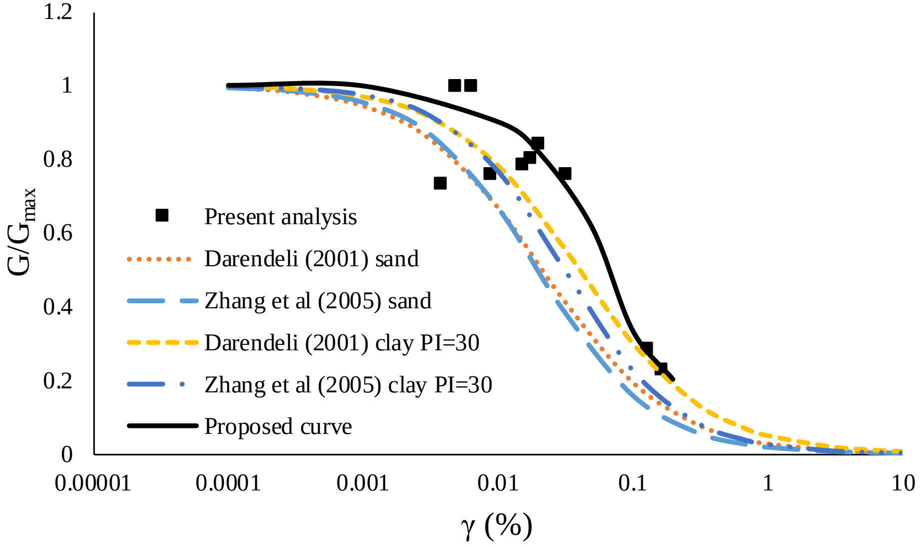


Figure 10: back computed G/G_{max} values

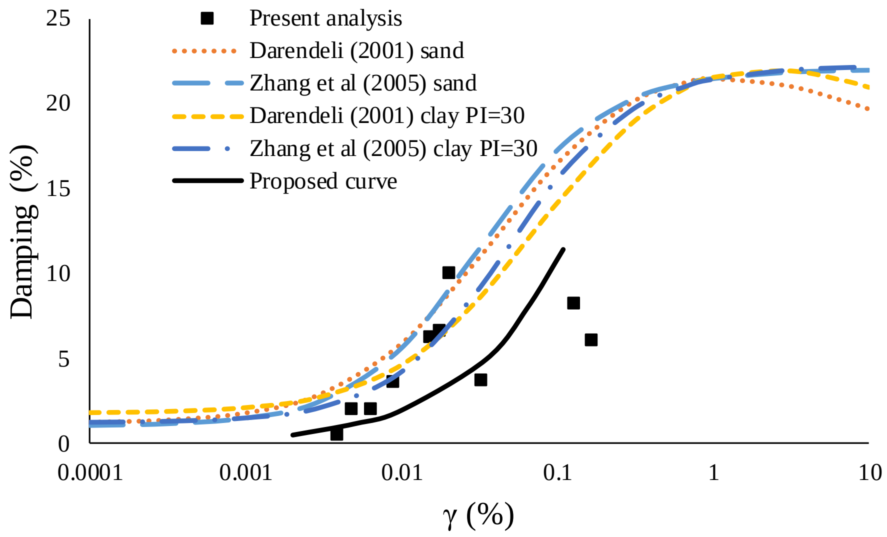


Figure 11: back computed β values

Ref: Mondal and Kumar (2023)

Thank You