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SITE RESPONSE ANALYSES BASED ON SITE SPECIFIC SOIL PROPERTIES USING GEOTECHNICAL AND GEOPHYSICAL TESTS: CORRELATIONS BETWEEN G_{MAX} AND N_{60}

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ABSTRACT

In this paper an attempt has been made to compare ground response of overburden soil using geotechnical and geophysical methods in Bangalore, India for a selected input motion. The study area has 122’0”x190’0” is located at southeastern side of Bangalore city, in front of the Bangalore International airport. A geotechnical investigation and geophysical testing have been carried out at five locations in the selected site. At same locations, geophysical investigations have been carried out using multichannel analysis of surface waves (MASW) method. Both 1D and 2D shear wave velocity profiles have been obtained. The synthetic earthquake generated for the maximum credible earthquake (MCE) has been considered for the site response analysis. The SHAKE2000 has been used, for the site response study by considering the ground motion (synthetic earthquake) data and geotechnical parameters such as shear-wave velocity, density and “N” value. The comparison of the both test results are discussed in this paper and also the correlation between corrected SPT “N” values to the G_{max} using MASW has been generated.

Keywords: Site response, SPT, MASW, SHAKE2000 and G_{max} relation

INTRODUCTION

Southern India once considered as a stable continent has recently experienced many earthquakes indicating that it has become moderately seismically active region. Study of seismic hazard and ground response is essential and has become mandatory for the design of important structures. Predicting site response is an important step in estimating the effects of earthquakes since local ground conditions substantially affect the characteristics of incoming seismic waves during earthquakes. Site response study is usually carried out using the geotechnical data (SPT “N” Value) or Geophysical data (shear wave velocity), but there is no clear guideline as to which one is best for a particular site condition. An attempt has been made to carry out ground response analysis by conducting field SPT and MASW tests. The 1D ground response study has been done using SHAKE2000. The selected site is located in the south eastern side of international airport, Bangalore, India. For assessing seismicity of the area the deterministic seismic hazard analysis (DSHA) carried out by Sitharam and Anbazhagan (2006) has been used. The synthetic ground motion generated and dynamic soil properties from the field-testing are used for one dimensional ground analysis to study the site response of soil columns. The amplification of soil columns, peak horizontal acceleration variations and spectral acceleration both at rock level and ground surface have been studied and presented in this paper. An attempt has been made to generate G_{max} relation with SPT “N” value.

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SITE DESCRIPTION

The proposed facility along with locations of standard penetration testing (SPT) and Geophysical investigations are shown in Figure 1. The site rock formation is comprised of Gneissic complexes formed before 2700 to 2500 million years, formation identified as Sargur Group of rocks, which is followed by peninsular gneissic complex.

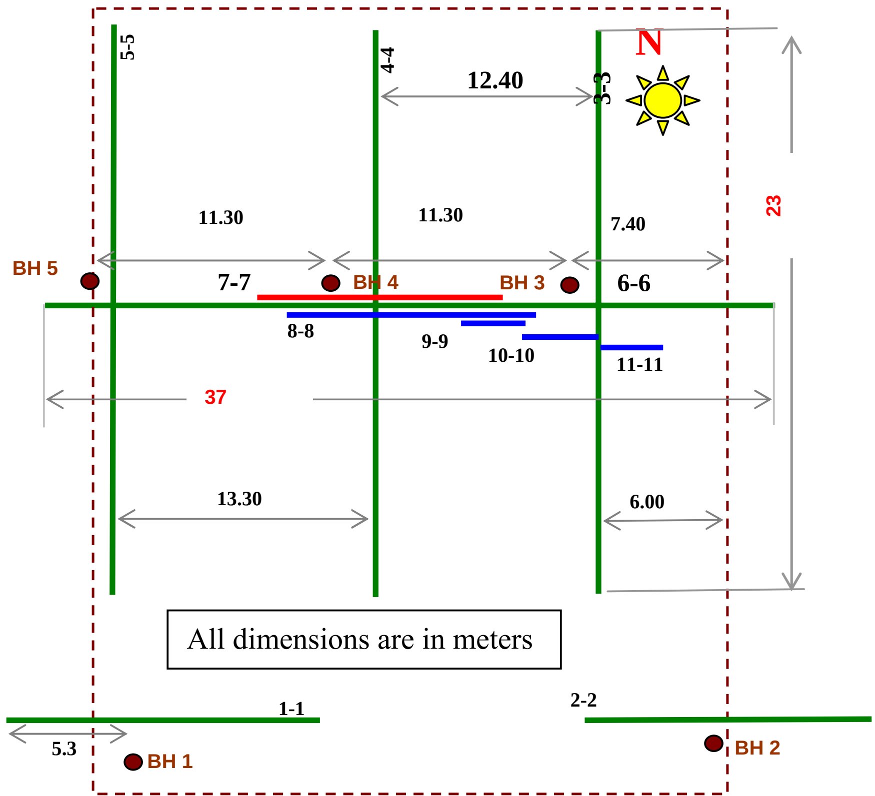


Figure 1: Site Map with marked testing locations

Geotechnical Investigations

The SPT testing was carried out at five locations in such a way that they are distributed through out the construction area and represent the site characteristics (see Figure 1). Five bore holes of 150mm diameter up to the rock depth has been drilled using Rotary hydraulic drilling. SPT tests results shows the general soil profile consisting of a variable thickness of soil overburden, which can be classified as filled up soil extending to a depth of 2m to 2.3m in different locations. The field "N" value for the filled up soil layer varies from 8 to 24 at different borehole locations. In the borehole BH-3 to BH-5 clayey sand is present below the filled up soil or at the top itself having a liquid limit of more than 35. Below this layer, a silty sand layer with clay or without clay is present to a depth of 9.0m to 16m. The field 'N' value for this silty sand layer varies from 19 to 75. The disintegrated weathered rock exists below the silty sand layer having a refusal strata with N>100. The thickness of the overburden varies from 3.5m to 16.5m from ground level at different borehole locations. Below the disintegrated weathered rock, weathered / hard rock exists. The core-recovery of the weathered / hard rock samples (except in BH-5) is reported to be more than 75%. The rock formation is classified as granitic gneiss without faults and fissures. Water table in this area during the investigation is at about 1.5m below the ground level in all the boreholes, typical bore log is shown in Figure 2. The "N" values measured in the field using standard penetration test procedure have been corrected for various corrections, such as:(a) Overburden Pressure (C_N), (b) Hammer energy (C_E), (c) Bore hole diameter (C_B), (d) presence or absence of liner (C_S), (e) Rod length (C_R) and (f) fines content (C_{fines}) (Seed et al.; 1983, Skempton; 1986, Schmertmann; 1978, Sitharam et. al, 2005). Field "N" is corrected using the following equation and Corrected "N" value i.e., (N_{60}) is obtained:

$$N_{60} = N \times (C_N \times C_E \times C_B \times C_S \times C_R \times C_{fines}) \quad (1)$$

BORE LOG

Location	Institute of Arospace Medicine	Date of commencement	16.11.2005
BH No	3	Date of completion	18.11.2003
		Ground Water Table	1.5m

Depth Below GL(m)	Soil Description	Thickness of Strata (m)	Legend	Details of Sampling		SPT N Value
				Type	Depth (m)	
0.0	Filled Up Soil			SPT	1.5	1/1//0 N=2
1.0				UDS	2.5	
2.3		2.3				
3.0	Reddish /Grayish Clayey sand	0.7		SPT	3.0	10/9//10 N=19
				UDS	4.5	
4.5	Greyish silty sand/ Sandy silt with mica			SPT	5.0	12/14/2025 N=39
6.0				SPT	6	30/48/53 N=101
8.0				SPT	7.5	75R for 3cm Penetration
9.0		6				
10.0	Weathered Rock 9m to 10.5m CR=76%,ROD=43%			SPT	9	75R for no Penetration
10.5		1.5				

Bore hole Terminated at 10.5m

Note
SPT Standard Penetration Test
UDS Undisturbed Sample
R Rebound

Geophysical Investigations

MASW is a geophysical method, which generates a shear-wave velocity (Vs) profile (i.e., Vs versus depth) by analyzing Raleigh-type surface waves on a multichannel record. MASW has been effectively used for identification of broadband width and highest signal-to-noise ratio (S/N) of surface waves. MASW system used for this investigation consisting of 24 channels Geode seismograph with 24 geophones of 4.5 Hz capacity. The seismic waves are created by impulsive source of 10 pound (sledge hammer) with 1'x1' size hammer plate with ten shots, these wave are captured by geophones/receivers. The captured Rayleigh wave is further analyzed using SurfSeis software. SurfSeis is designed to generate Vs data (either in 1-D or 2-D format) using a simple threestep procedure: i) preparation of a Multichannel record (some times called a shot gather or a field file), ii) dispersion-curve analysis, and iii) inversion. The 1D MASW test has been carried out corresponding to 5 borehole locations (BH-1 to BH-5) with 25 recording points. The spread length locations are shown in Figure 1 as survey line 1-1 to 5-5. The multichannel analysis of surface wave (MASW) spread length was selected in such a way that the mid point of the MASW spread length matches with the SPT borehole points. The optimum field parameters recommended by Park et. al (1999) (source to first and last receiver, receiver spacing and spread length of survey line) are selected in such a way that required depth of information can be obtained. All the testing has been carried out with geophone interval of 1m and source to first and last receiver is varied from 5m, 10m and15m.

2D velocity profiling has been carried out to verify the rock dipping direction and ground anomaly. To get the 2D profile, a multiple number of shot gathers are acquired in a consecutive manner along the survey line by moving both source and receiver spread simultaneously by a fixed amount of distance after each shot. Each shot gather is then analyzed for 1-D Vs profile in a manner previously stated. In this way a multiple number of Vs profiles are generated. The Vs data are assigned into 2-D (x-z) grid. Various types of data processing techniques can be applied to this 2-D Vs data. A countering, a simple interpolation, data smoothing, or combination of these may be applied at this stage. When the Vs data are assigned to the grid, there is ambiguity in the horizontal coordinate (x) to be assigned because each Vs profile was obtained from a shot gather that spanned a distance too large to be considered as a single point. It seems reasonable that the centre of the receiver spread be the most appropriate point because the analyzed Vs profile represents an average property within the spread length (Park et. al, 2005). 2D MASW test has been carried out along survey line 6-6 with 13 recording points, which is shown in the Figure 1 as line 6-6. The results of 2D profile have been presented for the location of line 7-7.

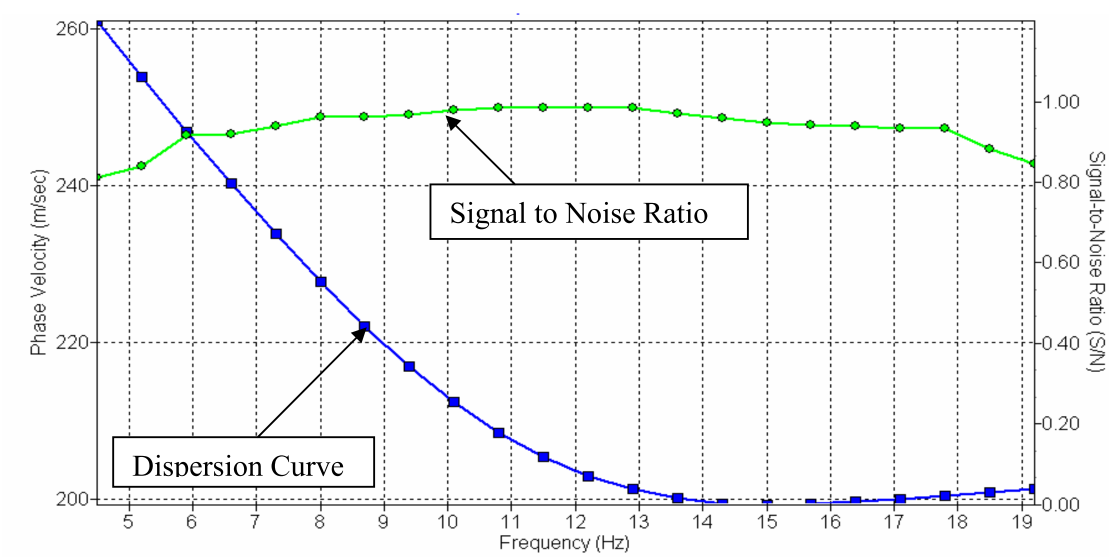


Figure 3: Typical Dispersion Curve obtained from MASW for Line 5-5

The generation of a dispersion curve is a critical step in all MASW survey. A dispersion curve is generally displayed as a function of phase velocity versus frequency. Phase velocity can be calculated from the linear slope of each component on the swept-frequency record. The lowest analyzable frequency in this dispersion curve is around 4 Hz and highest frequency of 35Hz has been considered. Typical dispersion curve is shown in Figure 3 for the location 5-5, each dispersion curve obtained for corresponding locations has the high signal to noise ratio of 80 and above. A Vs profile has been calculated using an iterative inversion process that requires the dispersion curve developed earlier as input. A least-squares approach allows automation of the process (Xia et al., 1999) as inbuilt in

SurfSeis. Vs have been updated after completion of each iteration with parameters such as Poisson's ratio, density, and thickness of the model remaining unchanged. An initial earth model is specified to begin the iterative inversion process. The earth model consists of velocity (P-wave and S-wave velocity), density, and thickness parameters. Typical 1D Vs and Vp profiles are shown in Figure 4 for the location of 1-1. Velocity calculated at mid point of each survey line is comparable with the borehole location because the survey line mid point is coinciding with the borehole location. The shear wave velocity values obtained from each survey line for the different layers falls within the recommendations of NEHRP "Vs"- soil classification of site categories (Martin, 1994) and IBC code site classification (IBC-2000). A layer with a shear wave velocity of more than 360 m/sec is considered as a weathered rock. It can be noticed that the weathered rock formation is met at 14.0m corresponding to lines 1-1, 6.0m for line 2-2, 9.0m for line 3-3, 11.0m for line 4-4 and 28.0m for line 5-5. For the hard to very hard rock, the shear wave velocities > 760 m/sec and is met at 36.0m for line 1-1, 16.5m for line 2-2 and 25.0m for line 3-3. The hard rock is not encountered up to 50 m corresponding to line 4-4 and even up to 40 m corresponding to line 5-5. These observations of 1D Vs profiles compare very well with the bore log data. The 2D velocity profile has been used to find the layer thickness, subsurface anomaly and rock dipping directions. Typical 2D velocity profile for the line 7-7 is shown in Figure 5. Figure 5 shows that there is no considerable ground anomaly present in the line, however there is a slight reduction in velocity at mid point of the line. Reduction in velocity is due to presence of lose silty sand in borehole location (BH4) and this is confirmed during excavation of the site for constructions. The weathered rock velocity ranges are at shallow depth at left side of the line (Eastern side) and at deeper depth on right side (Western side) of line 7-7. The rock dipping observed in MASW match well with the SPT borehole observation.

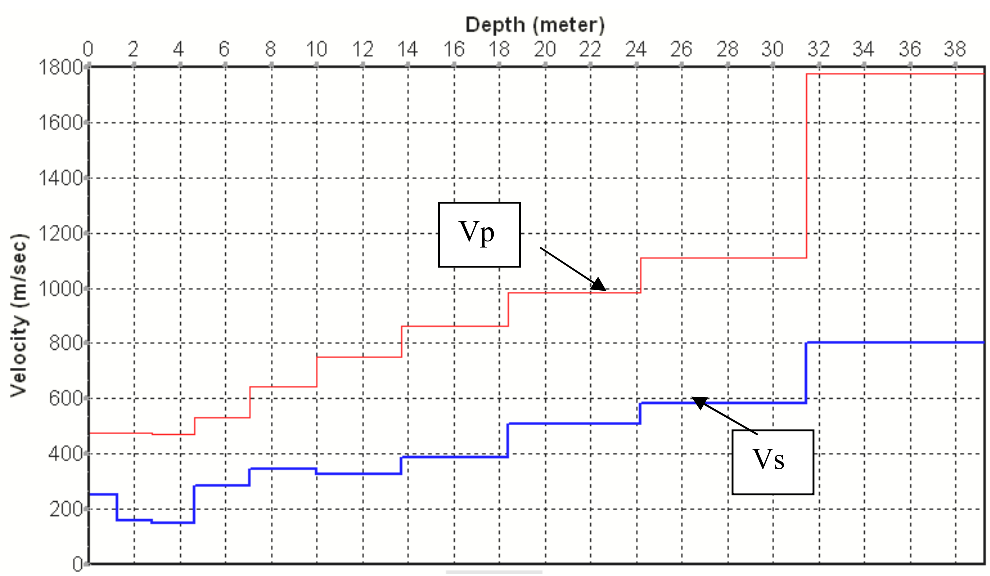


Figure 4: Typical Vs and Vp Plots for Line 1-1

GROUND RESPONSE ANALYSIS

For the ground response of soil column for a given input ground motion data is evaluated using 1D ground response analysis software SHAKE 2000. SHAKE2000 calculates the expected ground movement by combining wave propagation theory with material properties and seismic input motion. The geotechnical parameters like soil type, thickness of the layer, unit weight of the material, shear modulus value of the material, shear wave velocity of the material and earthquake acceleration file is provided as input data. The common parameters of soil type, thickness of the layer, unit weight of the material have been obtained from geotechnical tests contacted but the shear modulus of the material is calculated using inbuilt equations in SHAKE2000.

The geotechnical investigations with SPT "N" values, laboratory results and MASW result of Shear wave velocity are used to evaluate max shear modulus value of the material. The synthetic ground motion generated by Sitharam and Anbazhagan (2006) has been used as earthquake acceleration file at weathered rock level ("N">100 or Vs >395m/sec) in each analysis. Sitharam and Anbazhagan (2006) generated the synthetic ground motion using SMSIM- program for simulating ground motions, seismological model by Boore (1983, 2003). The strong motion data simulated for the Maximum Credible earthquake of Mw of 5.1 and vulnerable source of Mandya-Channapatna-Bangalore lineament having a length of about 105km with hypocenter distance of 15.88km. The synthesized ground motion has a PHA of 0.153g with predominant frequency of about 4 Hz at rock level. A transfer function is used as a technique for 1D ground response analysis. Here the time history of the bedrock (input) motion is in the frequency domain represented as a Fourier series using Fourier transform. Each term in the Fourier series is subsequently multiplied by the Transfer function. The surface (output) motion is then expressed in the time domain using the inverse Fourier transform. However the complex transfer function is only valid for linear behaviour of soils. Therefore this approach has to be modified to account for the non-linearity. The linear approach assumes that shear strength (G) and damping (ξ) are constant. However, the non-linear behaviour of soils is well known and can be determined very well in a laboratory environment. Shear strength reduces with shear strain, while damping increases with shear strain. The problem then reduces to determining the equivalent values consistent with the level of strain induced in each layer. This is achieved by using an iterative procedure on basis of these curves (Idriss and Sun, 1992, Slob et. al, 2002). Shear modulus and damping reduction curves are selected based on the soil prosperities available form geotechnical data, since the overburden soil for all the bore logs almost has similar properties, the curves proposed by (G/G_{max} - sand, average inbuilt in SHAKE2000) Seed & Idriss 1970 are considered for the silty sand, Similarly for rock material the shear modulus and damping curves proposed (G/G_{max} – rock inbuilt in SHAKE2000) by Schnabel (1973) have been used.

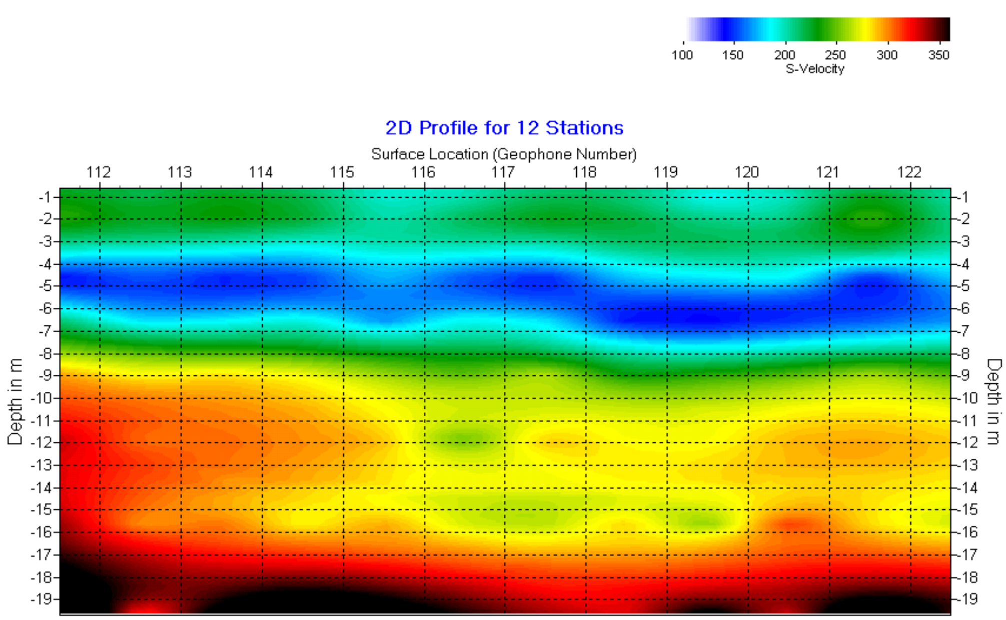


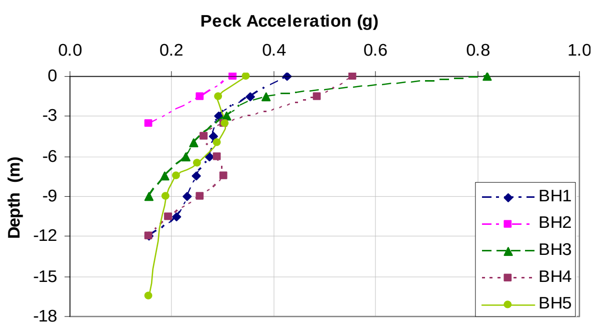
Figure 5: 2D Shear wave velocity Profile obtained for the Location7-7

Ground Response study using SPT "N" Value

Observed "N" values are corrected using the equation 1. The densities of the each bore log are evaluated form the undisturbed sample collected during the field testing. The inbuilt SHAKE2000 option1 to option 5 have been used to give the input parameters to the program, option 6 to option 11 have been used to get output data in a required format. From the "N_{60}" and computed densities for each bore log the max shear modulus has been calculated by using inbuilt SHAKE2000 equation number 13 (see equation 2) which is given below:

$$G_{\max}(kips/ft^2) = 325(N_{60})^{0.68} \quad \textit{(Imai and Tonouchi, 1982)} \qquad (2)$$

The shear wave velocity is back calculated from the well known equation of $G = \rho V_s^2$. Input ground motion has been assigned at bore hole termination level of "N">100 for weathered/hard rock. The given soil parameters are processed for the assigned input motion to obtain the Peak Acceleration, Acceleration time history, Stress and strain time history, Response spectrum, Amplification spectrum and Fourier Amplitude spectrum results. The site response study using geotechnical data shows that the PGA obtained is 0.82g for a given rock motion having PGA of 0.156g, indicating that the site is amplifying in nature. The peak acceleration of each layer for all bore logs has been shown in Figure 6. Figure 6 shows similar amplifying trend for the all bore logs except bore log 2 which has small overburden thickness and lesser number of layers. BH5 amplifies less compare to BH3, even though the overburden thickness of BH5 is higher. This is attributed to the soft material present in BH3. The predominant period of soil column of each bore log varies in between 0.04sec to 0.21sec due to variation in overburden thickness. Figure 7 shows predominant period of soil column for each bore log. The shape of the response spectrum curve matches well with the uniform hazard response spectra



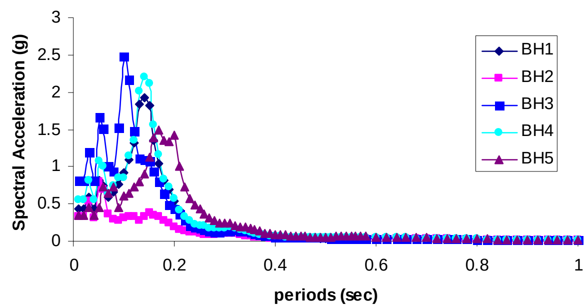


Fig 6: Peak Acceleration with depth using SPT Fig 7: Response Spectrum at surface using SPT

shape. Amplification spectrum gives the amplification ratio which is obtained as the ratio between the Fourier spectrums of the rock to the soil. Amplification ratio (frequency response function) has been used to identify the natural period of the soil column/site. Figure 8 shows the amplification ratio calculated using the SPT results, and indicates that the amplification ratio for all bore log soil column lies in between 10 to 15 except in BH2. In BH2 the amplification ratio peak may reach after 25Hz frequency, which may be due to the very thin soil column in the location.

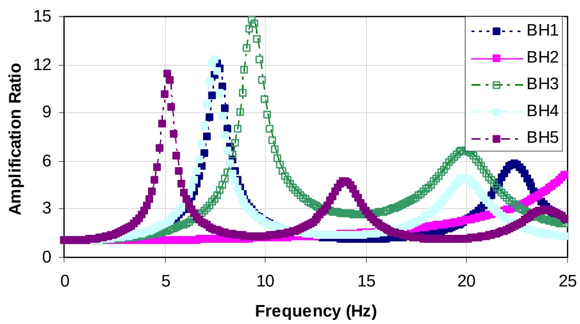
Ground Response study using MASW "Vs" Value

The response study using SPT "N" is based on G_{max} calculated from in built equation (equation no 2). In MASW test the calculation of G_{max} is simple, which is given below

$$G = \rho V_s^2 \qquad (3)$$

Where
ρ density measured from the undisturbed sample
Vs shear wave velocity measured using the MASW testing.

Many researchers used shear wave velocity from the MASW, SASW (spectral analysis of surface wave) and micro tremors data for site response study, (Borja et. al 2002;, Mirzaoglu and Dykmen 2003; Susanta Ghosh 2003; Tuladhar et. al 2004; Umut Dentegul 2004 and Rajiv Ranjan, 2005). The 1D shear wave velocity measurements at borehole location and density for laboratory testing has been given as inputs to SHAKE2000 program, as stated earlier and similar outputs are obtained. The peak acceleration at ground surface is obtained as 0.507g for given rock motion having peak acceleration of 0.156g using the "Vs" data. Figure 9 shows the PGA for all the bore logs using Vs data and clearly indicates a similar trend of amplification of the overburden. Amplification at BH5 is less when compared to BH2 and BH3 locations, Even though the overburden thickness of BH5 location is higher. This may be due to lower shear wave velocities at location BH5 when compare to BH3



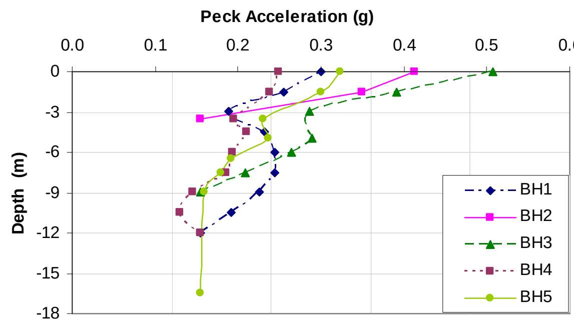
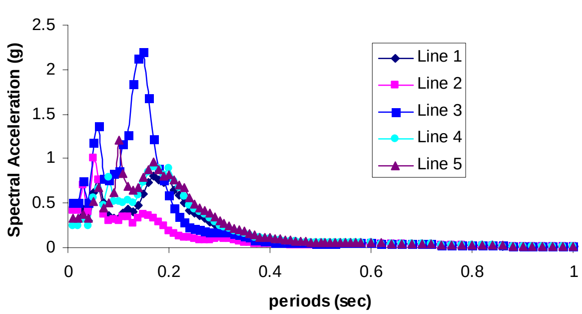


Fig 8: Amplification Ratio using SPT **Fig 9: Peak Acceleration with depth using MASW**

location. Shear wave velocity values at BH2 are almost corresponding to weathered rock; however this location gives higher PGA value when compared to locations BH1, BH4 and BH5. This may be attributed to the higher "Vs" values. The predominant period of soil column of each bore log varies in between 0.04sec to 0.23se due to variation in overburden thickness. Figure 10 shows predominant period of soil column for each location of bore log, the shape of the response spectrum curve matches with the uniform hazard response spectra shape. Also the spectral acceleration obtained for the site, matches well with the shape of the spectral acceleration curves presented in IS1983-2002. Figure 11 shows the amplification ratio calculated using the MASW tests. The amplification ratio of all bore log locations lies between of 8.5 to 11.5 except in BH2. At BH2, the amplification ratio had not reached peak value until the frequency of 25Hz, which may be due to very higher shear wave velocity at the location.

RESULTS AND DISCUSSION

The site response results form SHAKE2000 using the geotechnical and geophysical data are comparable. However SPT test gives higher values as G_{max} estimated is higher from equation 2. Figure 12 shows the variation of peak acceleration with depth for BH4 by considering both the analysis. Peak acceleration at ground level is 0.42g using SPT data and 0.30g using MASW data. The amplification trends are almost similar using SPT data and MASW data.



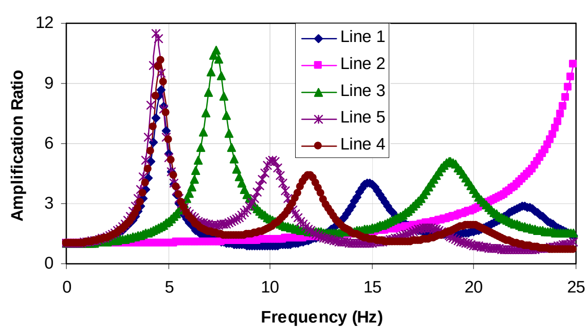


Fig 10: Response Spectrum at surface using MASW Fig 11: Amplification Ratio using MASW

Figure 12 shows that the PGA obtained using SPT data is higher that the using MASW data. This is attributed to G_{max} calculation using equation 2. Destegul (2004) carried out sensitivity analysis by varying the different input parameters using SHAKE2000. He found that increase in the depth (overburden thickness) causes decrease in acceleration values due to very thick sediments of same materials which will be stiffer than the thinner one. Figure 13 shows that increase in soil column thickness reduces the PGA value, which matches with the result presented by Destengul (2004).

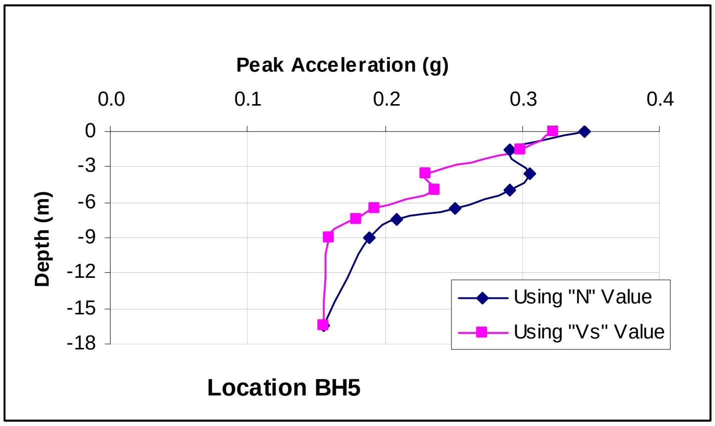
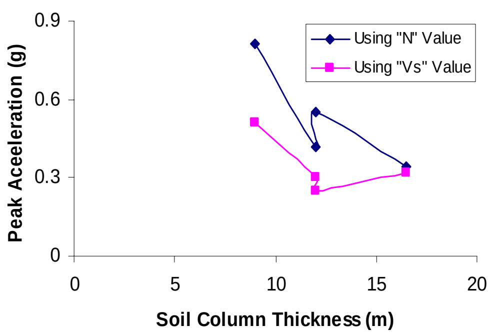


Figure 12: Peak Ground Acceleration with Soil Column Thickness



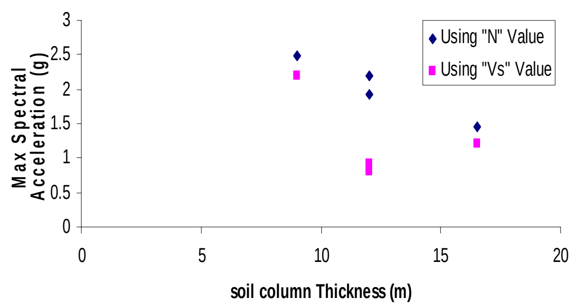


Fig 13: PGA with Soil Column Thickness **Fig 14: Maximum SA with Soil Column Thickness**

Figure 14 clearly indicates that maximum spectral acceleration values results from the SPT data. Typical Amplification ratio of soil columns are shown in Figure 15, amplification ratio varies from 9 to 15 based on the properties of soil column. Amplification ratio decays with frequency as shown Figure 15. Also similar trend is seen in all the bore logs for both the SPT and MASW data. Amplification ratio using SPT data is higher than that from MASW data except in BH5 where both are same (see Fig 15). Amplification ratio (AR) with soil column thickness is shown in Figure 16, which clearly indicates that similar trends as obtained for PGA and maximum acceleration value plots.

Figure 17 shows predominant period obtained from SHAKE2000 by using SPT and MASW data. The natural period of soil column obtained from SHAKE2000 using both the SPT and MASW data is shown in Figure 18. Figure 18 shows that the natural period increases with increase in the thickness of soil column. The natural period using SPT data is higher than that using MASW data. The predominant period (PP) is correlated with soil column thickness by fitting a linear function. It showed a very good regression squared values. R squared value for MASW data is 0.953 and SPT data is 0.946. The relation obtained using SPT data and MASW data are given below

Using SPT data: Predominant period (sec) $PP = 0.0124H - 0.0012$ (4)

Using MASW data: Predominant period (sec) $PP = 0.0116H + 0.0435$ (5)

Where, H is the height of the overburden soil in meter.

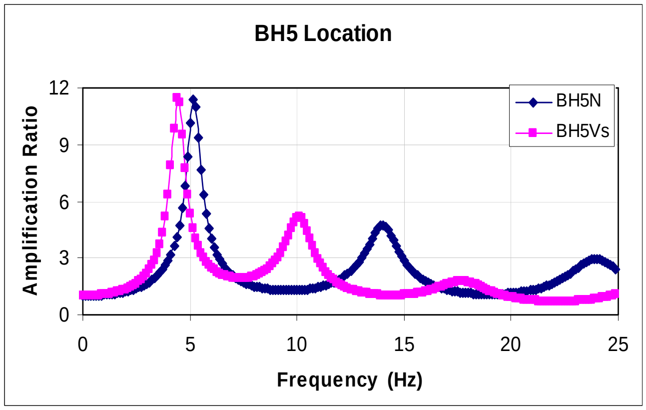
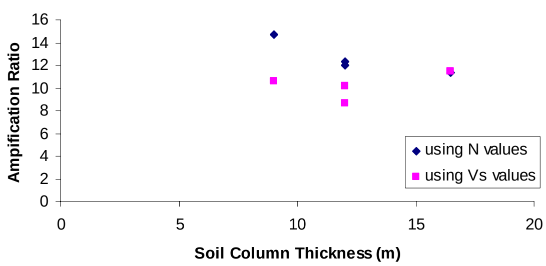


Figure 15: Amplification Ratio with Soil Column Thickness



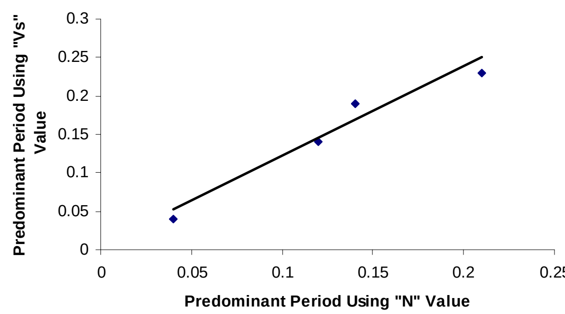
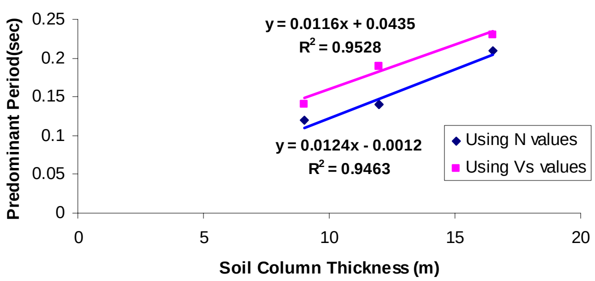


Fig 16: AR with Soil Column Thickness **Fig 17: Predominant Period using SPT & MASW**



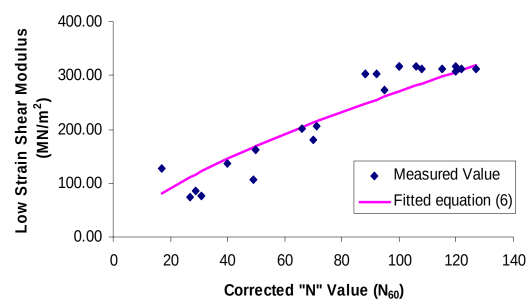


Fig 18: PP of soil columns with Thickness Figure 19: Correlation between G_{max} with N_{60}

From the above studies, it is clearly shows that the peak ground acceleration, maximum spectral acceleration and amplification ratio using SPT data is higher than the MASW data. High spectral acceleration may be attributed to presence of very large amount of fines (silt content) in top layers and properties of overburden obtained at high strain levels in geotechnical tests. Dynamic properties obtained from SPT test correspond to high strain values when compared to MASW test which gives properties at low shear strains. Also the factor affecting G_{max} are dependant on soil parameters, but in SHAKE2000 G_{max} is calculated based on the inbuilt equation (see equation no 2). This equation was developed for some other area based on soil present in that area. From this study it is felt that Shake program can be effectively used by using G_{max} equation for the region or the in-situ shear wave velocity for shake analysis. By considering this requirement the authors try to generate the relation between "N_{60}" with measured low strain G_{max} using MASW data.

RELATION BETWEEN G_{MAX} AND N_{60}

Studies show that the site response obtained from SHAKE2000 using MASW data is reasonably good when compared to using SPT data. However SPT technique is very common. The SPT data can be effectively used for site response analysis, if regional G_{max} equation is developed. To fulfil this requirement an attempt has been made to correlate the measured G_{max} to corrected "N" values using available data. The correlation obtained as given in equation 6, for the data shown in Figure 19 is as follows.

$$G_{\max} = 11.8(N_{60})^{0.68} \qquad (6)$$

Where, G_{max} –Low strain maximum shear modulus in MN/m^2,
N_{60} – Corrected SPT "N" Value.

Power regression fitting gives the highest R squared value of 0.93. Equation given in the Shake program (see equation 2) is 1.32times larger than proposed equation 6.

CONCLUSION

Geotechnical and geophysical investigations have been carried out at a site in Bangalore opposite to international airport. The observed "N" value is corrected following general seismic "N" correction procedures. MASW with SurfSeis has been used to calculate the shear wave velocity of soil profile in all the SPT locations. SHAKE2000 1D equivalent linear ground response analysis software has been used to determine the site specific response of the soil column by using SPT and MASW data separately. Response spectrum obtained from SHAKE2000 matches well with the shape of the spectral acceleration coefficient presented in IS1983, 2002 and uniform hazard spectrum. The obtained SHAKE2000 results from the both methods are compared. Relation between G_{max} with corrected "N" value (N_{60}) has been generated.

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