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R. Sreekala
Structural Engineering Research Centre-SERC, CSIR Campus, Taramani, Chennai, India

N. Lakshmanan
Structural Engineering Research Centre-SERC, CSIR Campus, Taramani, Chennai, India

K. Muthumani
Structural Engineering Research Centre-SERC, CSIR Campus, Taramani, Chennai 600 113,TamilNadu, India

N. Gopalakrishnan
Structural Engineering Research Centre-SERC, CSIR Campus, Taramani, Chennai 600 113,TamilNadu, India

K. Sathishkumar
Structural Engineering Research Centre-SERC, CSIR Campus, Taramani, Chennai 600 113,TamilNadu, India

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POTENTIAL OF VIBRATION STUDIES IN THE SOIL CHARACTERIZATION AROUND POWER PLANTS – A CASE STUDY

R. Sreekala
Structural Engineering Research Centre-SERC,
CSIR Campus, Taramani,
Chennai 600 113,TamilNadu, India

N. Lakshmanan, K. Muthumani, N. Gopalakrishnan , K. Sathishkumar
Structural Engineering Research Centre-SERC,
CSIR Campus, Taramani,
Chennai 600 113,TamilNadu, India

ABSTRACT

Propagation characteristics of waves generated by the various sources of vibration can be dependent on the type of the generated waves, which can be accessed by measuring particle motion in vertical, longitudinal and transverse direction. The monitoring of motion in three directions on the ground surface and in depth is important for the characterization of propagating waves. Vibrations of the machine foundations induce elastic waves in soil, which may affect surrounding buildings. Generally, the attenuation of vibrations on surface is composed of two factors namely geometric damping and material damping. The paper is an experimental investigation with regard to the ground vibrations and its attenuation during the operation of power plants. The study helps in characterizing the soil around a power plant. The investigation was carried out on two power plants, which runs at the same frequency, and soil characterization was done based on the study. Measurements were taken on the level ground for the harmonic waves generated from the diesel power plant. Study is found to be helpful in characterizing the soil based on the frequency independent material damping coefficients, low amplitude shear modulus etc. on the plant premises. The effect of these vibrations on adjoining areas can be well predicted based on the soil medium.

INTRODUCTION

Power plants are the necessary ingredients of national growth, thus becomes inevitable for the economic development of the country. The level of ground and structure vibrations caused by power plant structures depends on many factors including the characteristics of wave propagation at a site depending on the soil medium. Due to rapid industrialization the issue of the vibration problems in structures around power plant is also increasing. A thorough understanding of the attenuation characteristics of vibrations in soils is helpful in solving many of the problems around the plant periphery. Machines running at low frequencies like reciprocating type require special attention because control of vibration in a later stage through trench isolation is impossible and alternative methods are tedious to execute. So the knowledge regarding the attenuation characteristics of periodic vibrations through the soil is very important for the planning and development activity. In this study the ground vibrations and its attenuation during the operation of the power plant is considered. The ambient vibration data due the running of the generator were collected using acceleration pick-ups connected to a Fast Fourier analyzer. Measurements were carried out on four outwardly radiating lines at an interval of 10m starting from the DG house periphery. As vertical amplitude attenuates less and continues to exists for large distances compared to horizontal amplitudes, vertical components are selected for the study. The vibration through the soil is found to follow the Bornitz equation and thus the attenuation coefficient for material damping is determined. Further frequency independent attenuation coefficient is determined and the values are found to be quite reasonable for the soil type of the sites considered. Various studies carried out by different investigators are examined with respect to the present study.

ATTENUATION OF VIBRATIONS

Most of the vibratory energy affecting structures nearby is carried by Rayleigh(surface) waves traveling from the source of vibration. Generally, the attenuation of vibrations with surface is composed of two factors namely geometric damping and material damping. A portion of this attenuation is caused by the distribution of constant amount of vibration energy on continuously increasing area of wave front. This type of damping is called radiation/geometric damping. The geometric damping depends on the type and location of the vibration source and the material damping is related with ground properties and vibration amplitude. The decay of vibration amplitude with depth is shown in fig.1.It is clear from the figure that most of the higher amplitudes are concentrated near the surfacial layers.

The amplitude of vibration attenuates as the distance from the source of vibration increases. A portion of this attenuation is caused by the distribution of constant amount of vibration energy on the continuously increasing area of the wave front. This type of damping is called radiation damping and is usually described by the following equation :

$$w_2 = w_1\left(\frac{r_1}{r_2}\right)^n \tag{1}$$

where ‘w1’ is the amplitude of vibration at distance ‘r_1’ , ‘w_2’ is the amplitude of vibration at distance ‘r_2’ from the source and ‘n’ is the attenuation due to radiation damping. The value of the attenuation coefficient ‘n’ depends on the type of seismic wave and the position and size of the seismic source. Geometric damping occurs even in a partially elastic media. Kim et al, 1998 gives the value of ‘n’ for various combinations of source position and size.

Since the ground is not perfectly elastic, the vibration energy is reduced due to the friction and cohesion between soil particles. The attenuation due to material damping is affected by the soil type and frequency of vibration (Drabkin et al,Taniguchi et al). The combined effect of radiation damping and material damping can be described by the following equation.

$$w_2 = w_1\left(\frac{r_1}{r_2}\right)^n e^{-a.(r_2 - r_1)} \tag{2}$$

where ‘a’ is the attenuation coefficient due to material damping . Equation (2) is known as “Bornitz Equation” and is used when the amplitude of vibration is known at a small distance ‘r’ from the source. Damping of any vibrating system is a complicated parameter, and it is particularly so for foundation vibration resting on the soil. Damping of vibrating foundations consists of two parts, namely, material damping and radiation damping. Material damping is due to the hysteresis effect on the material and radiation damping is due to dissipation of energy within the unbounded soil medium. Material damping of soil ranges between 1 and 10% of the critical damping depending on material type, whereas radiation damping depends on several factors, and its value can be as high as 50% of the critical damping. Based on the results of measurement of man-made ground vibrations, researchers (Woods and Jedele, 1985) have reported recommended values of attenuation coefficient ‘a’ for soil materials. Values of ‘a’ recommended by Woods and Jedele for two values of vibration frequency (5 and 50 Hz) are given in Table.1. Subsequently Woods (1997) provided ranges of blow count values N_{SPT} , for each of the four classes of soils which are also included in Table.1.

TABLE 1 – Values of frequency dependent attenuation coefficient ‘a' for four classes of soil materials

Class	Material damping coefficient a (m^{-1})		Description of material
	5Hz	50Hz	
I	0.01-0.03	0.1-0.3	Weak or soft soils(N_{SPT}<5)
II	0.003-0.01	0.03-0.1	Competent soils(5<N_{SPT}<15)
III	0.0003-0.003	0.003-0.03	Hard soils(15<N_{SPT}<50)
IV	<0.0003	<0.003	Hard, competent rock(N_{SPT}>50)

The surface waves can travel only in the vicinity of the ground surface and may be out of plane Love waves (L-waves) or in-plane Rayleigh waves (R-waves). The L-waves are horizontally polarized shear waves and they exist only when there is a surface low-velocity layer on top of a higher velocity layer. Their velocity of propagation does not differ appreciably from that of S-waves. The propagation velocity of R-waves, V_R ,is slightly lower than V_S and their particle motion has both horizontal and vertical components. In a homogenous half space, the R-waves are non-dispersive (kim et al,1998). In case of layered elastic half space the propagation of Rayleigh-waves becomes more complex and it is found that R-wave velocity is frequency dependent. A simplified analysis of the mechanics of wave propagation in the ground leads to the following equation

$$a = \frac{2\Pi fD}{V_R} \tag{3}$$

where V_R is the propagation velocity of R-waves or the phase velocity, D is the damping ratio of the geo-material and *f* the frequency of vibration. Wave propagation due to machine foundation vibrations generate low strains where the soil can be assumed as a linear elastic medium. A number of theoretical solutions were formulated successfully with this approach (Barkan 1962,). The value of shear wave velocity of geo materials decreases with increasing values of cyclic shear strain. However, for cyclic strain amplitudes less than 10^{-5}, the value of Vs remains practically constant (Athanasopoulos et al,2000). In this case it is denoted by V_{so} and termed ‘’low amplitude shear wave velocity’’.

Low amplitude shear wave velocity of soil (V_{SO}) can be used as an index of ground stiffness. Athanasopoulos (1995) proposed an empirical correlation which can be used for all types of soils

$$V_{SO} = 107.6\left(N_{SPT}\right)^{0.36} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..(4)$$

where V_{SO} is the low amplitude shear wave velocity of soil(m/s) and N_{SPT} the uncorrected value of blow count of the standard penetration test. The in situ value of the damping ratio, D, however, cannot be known with the appropriate accuracy and this imposes a limitation in using equation (3) for estimation of values of attenuation coefficient, *a*.

So a'' frequency-independent'' coefficient of attenuation , a_0 , can be defined by writing equation(3) in the form

$$a_0 = \frac{a}{f} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(5)$$

where a_0 is the frequency-independent attenuation coefficient having units(s/m)

Yang (1995) has reported values of a_0 coefficients for soils ranging from loose sands and soft clays to rocks. These values range from 2x 10^{-3} s/m for soft soils to 3.65 x 10^{-4} s/m for rocks. As per Woods and Jedele, the values in the case of rocks is higher for Yang (1995) but in soft soils the values are same for both (fig.6).

MEASUREMENT

Four radiating lines were selected around the periphery of the DG house to conduct the vibration attenuation study. The method adopted is similar to SASW technique- spectral analysis of surface waves. Since a continuous vibrational source was available, the tri axial components of the vibration were captured at intervals on radiating lines. In most applications, vertical components are captured [Athanasapoulos et al, 2000] in surface vibration measurements as they attenuate slowly. The attenuation characteristics of the waves were studied.

A 5 cm cubical iron block weighing 988 grams with a 16mm rod having a pointed edge was driven to the soil at each of these locations. Tri-axial accelerometer pick ups were kept on top of this cube and signals were measured in vertical, longitudinal and transverse directions. The signals were captured in a portable FFT analyzer equipped with data acquisition and further storage. All measurements were conducted in level ground and far from underground obstacles that could have modified the wave field and the measured response at the position of the receivers. Towards estimation of attenuation of vibration values from the source of disturbance in soil, the radiating lines were chosen parallel to each of the global directions like North, South, East and West. The measurement was carried out starting at a distance of 15 meters from the source point and extended up to 100 meters at an interval of 10m while all the seven units were running.

Two sites were selected for the measurement purposes, in which DG-power plants were operating at 8 Hz. frequencies. From the vibration studies conducted, the values found for material constants were used to get the low amplitude shear wave velocities of soil. The soil types of both the sites values were found to be very well matching with the obtained result in terms of SPT in the soil report. For the case study 1(site1) the soil conditions around the plant are as given below

Soil conditions around the plant for Site no:1

Soil investigation report reveals that on an average the top 1m thick layer is filled up material consisting of coal cinder. Table 2. gives the soil conditions around the plant. The Ground Water Table (GWT) was encountered at an average depth of about 6.0 m below GL. The area investigated is made into six zones (fig.2) and in each zone the soil profile is reported. Throughout the area top 1m to 1.5m is filled up material consisting of coal cinder which cannot be densified. Bore hole locations in zone 1 and 2 indicates that the average SPT value up to 4m depth is 10(fig.3). Brownish to whitish dense to very dense silty fine sand with conglomerated pebbles is seen below 4m. The GWT encountered at a depth of 5.5 m below E.G.L. At bore hole locations 11 and 12 (zone 4) the SPT value is 21 and the GWT is below 6.4m (fig.4). Bore holes 23 and 24 indicates (zone 5) an SPT value of 33 with GWT below 7m fig.5). Here the coal cinder depth is 0.5m and somewhere it is not seen at all. But for boreholes 21, 25, 26 (zone 6) the coal cinder extends up to 1.5m.

The clayey soil (inorganic clays of high plasticity as per IS classification) encountered at almost all the locations is of swelling nature as observed from the laboratory tests. The free swell index is as high as 100 percent, for clayey soils indicating the swelling nature. For the .clay stratum encountered, the SPT values are found to be > 15.

Table-2- Soil Profile at the Measurement Location for Site No:1.

Distance below G.L. In meters	Type of Soil
1	Coal cinder
1-2.5	Brownish loose silty sand with conglomerated pebbles
2.5-5	Medium dense to dense silty sand
5-7	Stiff to hard sandy silty clay with conglomerated pebbles
After 7 m	Dense to very dense silty sand

INFERENCES DRAWN FROM THE STUDY

Soil vibration measurements around the plant on both the sites showed a dominant frequency of vibration equal to the operating frequency of the machine. Analysis of the experimental attenuation curves done and the values of geometric damping coefficients were arrived. Fig-1 shows the attenuation curves at 8Hz. in three orthogonal directions along four radiating lines, namely towards east, towards west, towards north and towards south. It is observed that the vertical amplitude attenuates less compared to lateral amplitudes and continues to exist for large distances. Also shown over-laid on the graph are the experimentally measured values. Table.3. gives the values of geometric damping coefficients (n). The frequency independent attenuation coefficient (a_0) is calculated from the experimental data by curve fitting using equation (2) and the values are tabulated in Table.4. The values suggest that the soil for site 1 is a combination of Woods-1997 and Yang -1995 classification for soft clays and loose sands. The upper bounds and lower bounds are prescribed by a recent study by Athanasopoulos et al (2000). Fig.6. shows the results of the available studies by various researchers. The shear wave velocity of the soil in site 1 is found to be 140-280 m/s, which is the upper limit for the obtained a_0 values as per the chart (fig 7). As per Barkan 1962, the velocities of surface waves are mostly in the range from 100 to 250 m/s.

For site 2, the a_0 values are computed based on the soil vibration study. Using chart, the soil is found to have low amplitude shear wave velocities in the range 250 to 560 m/s. Fig.7.gives the range of shear wave velocities for both the sites. As per Woods classification it is a combination of soil type of class II to IV. The SPT values are more than 15 in this case, and in some places it is found to be more than 50.

Using the empirical relation Eq.(4) to find the low amplitude shear wave velocity , the SPT values are found to be in the range 5-10 in the surfacial layers.. The soil investigation report also gives similar values as shown in fig.3. Bore hole locations 1 to 4 (zone 1) which corresponds to the western side of the plant, average SPT value is 10 as per the soil report. So the classification of soil based on frequency in-dependent material damping coefficient is very much useful in predicting the soil stiffness which is a function of low amplitude shear wave velocity (V_{s0}). It is established from the present study that in the case of periodic vibrations from power plants, the soil attenuation characteristics follows Biot's law and the classification of soils can be done based on the frequency independent material damping coefficient. As velocity of propagation of waves through soil is vital information regarding the vibration problems of the adjacent buildings, the study helps to predict the vibration amplitude for multiple frequencies at varying distances including sub harmonics in the case of saturated soil.

TABLE .3. Value of Geometric Damping Constant 'n' worked out through curve-fit of Measured Values

8 HzComponent Vertical	Towards east	Towards west	Towards north	Towards south
Site 1	0.15	0.77	0.39	0.29
Site 2	0.48	0.18	0.762	0.63

TABLE .4. Value of frequency independent material damping coefficients (a_0) computed during the study
a_0(s/m)10^{-3}

8 HzComponent Vertical	Towards east	Towards west	Towards north	Towards south
Site 1	1.5	2.25	3.0	3.38
Site 2	1.75	0.75	0.35	2.9

CONCLUSIONS

In this study, the ground vibrations in all the three directions induced by a running power plant are measured. From the study it can be concluded that for ground vibration developed from a periodic vibrating source (low frequency reciprocating type machinery), the attenuation follows Bornitz equation. Characterization of soil is done for the sites considered. The chart given by thanasapoulose et al. with the upper bound and lower bound limits are suitable for soil classification based on low amplitude shear wave velocity. The frequency independent attenuation coefficient can be used for setting the vibration limits for buildings for varying distances depending on the soil type. For the cases studied, it has been proved that, vertical amplitude attenuates less compared to lateral amplitudes and continues to exist for large distances.

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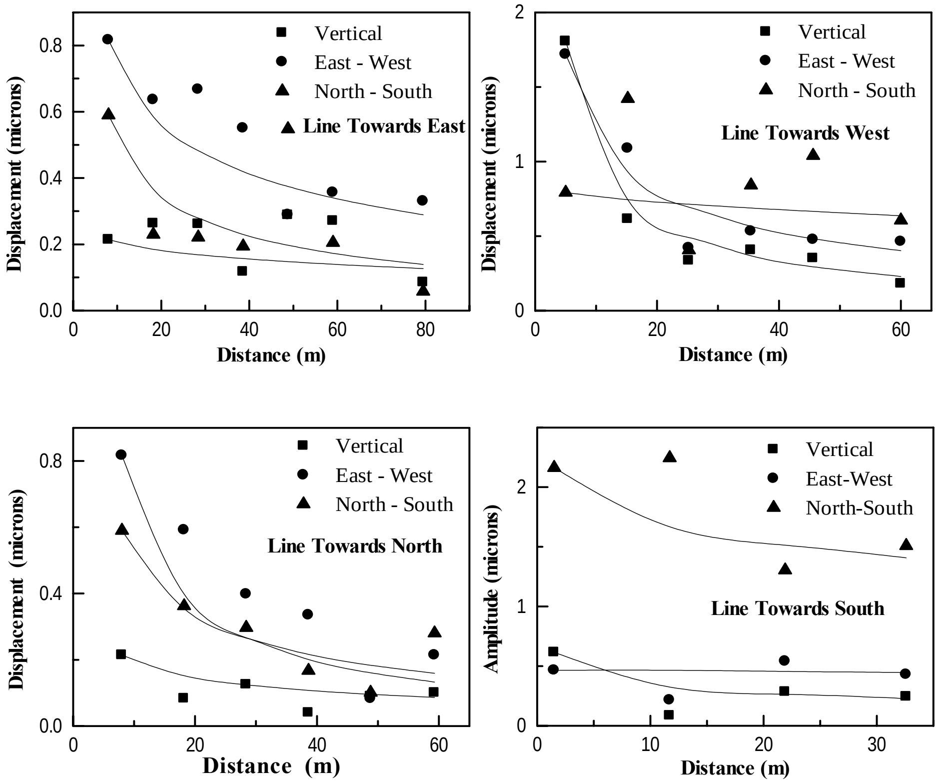


Fig-1 Steady -State Dynamic Displacement Variation against distance

- locations of the borehole log which is described in fig 3 &4

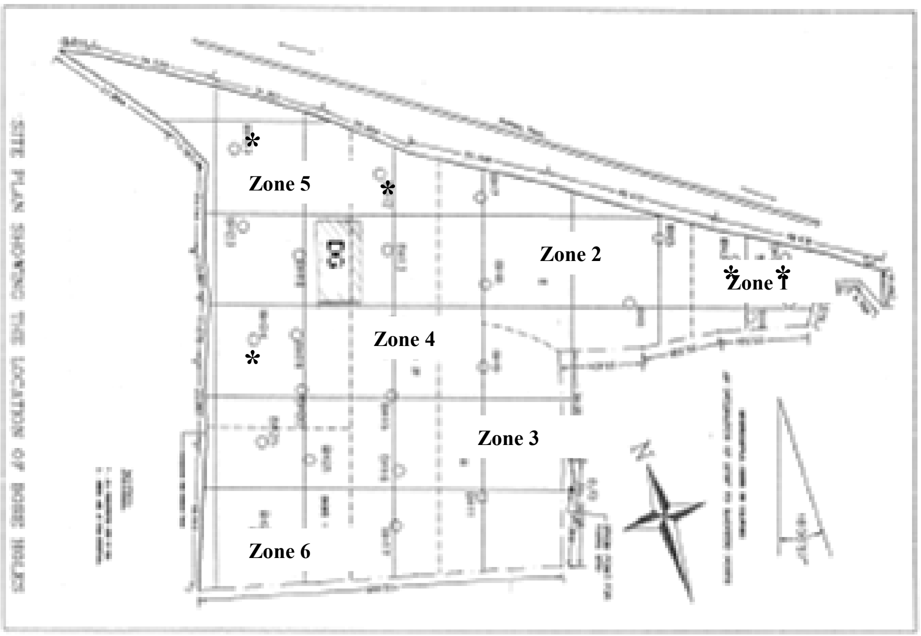
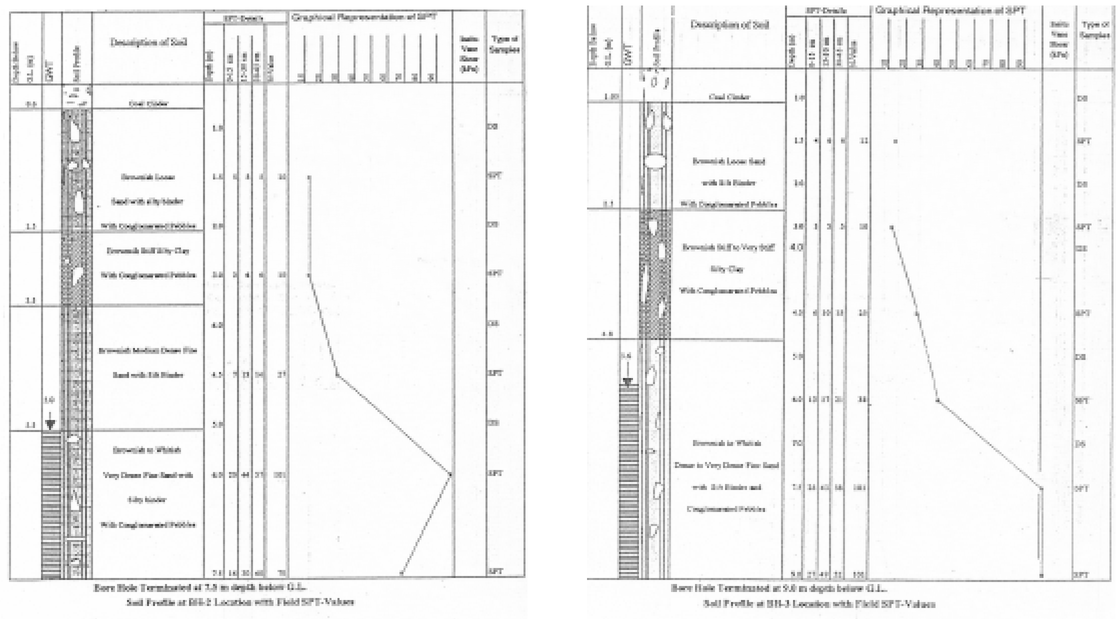


Fig.2. Site plan showing the location of boreholes



Bore Hole Terminated at 7.5 m depth below G.L.
Soil Profile at BH-2 Location with Field SPT-Values

Bore Hole Terminated at 9.0 m depth below G.L.
Soil Profile at BH-3 Location with Field SPT-Values

Fig.3. Soil profile at BH-2 and BH-3 locations with field SPT Zone 1)

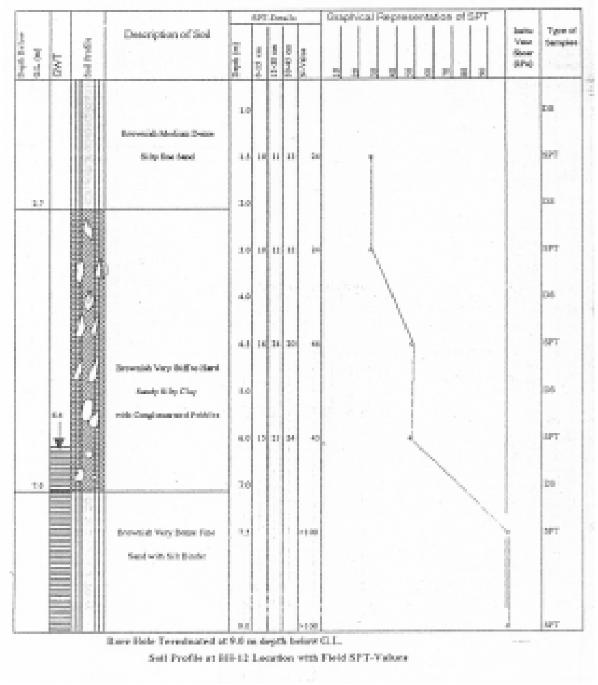


Fig. 4. Soil profile at BH-12 location with field SPT values

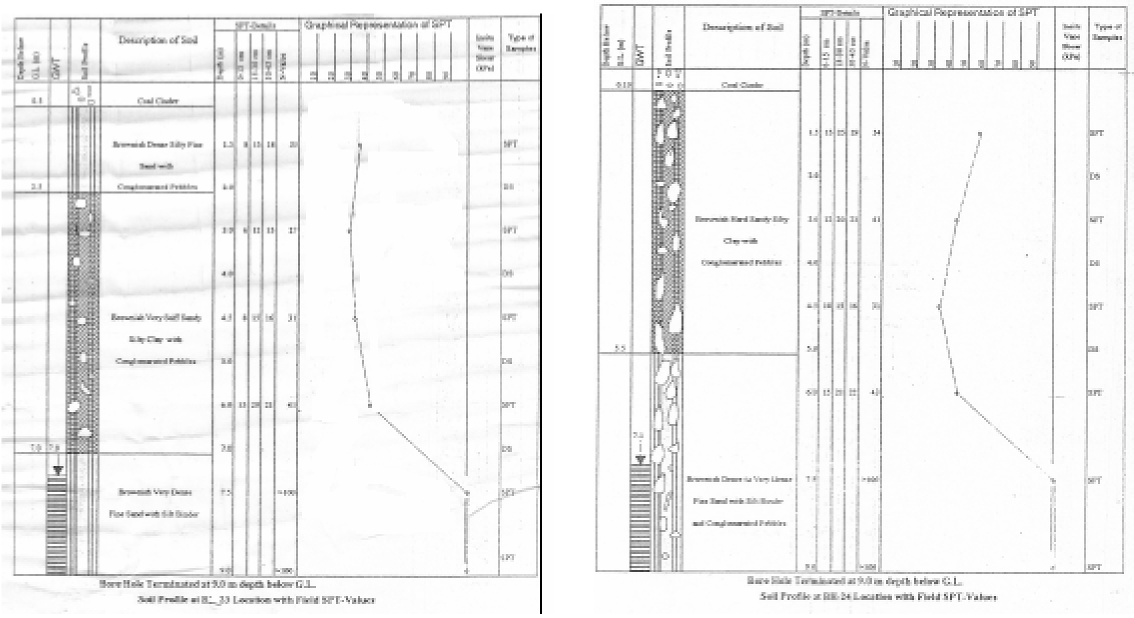


Fig.5. Soil profile at BH-23 and BH-24 locations with field SPT values (Zone 5)

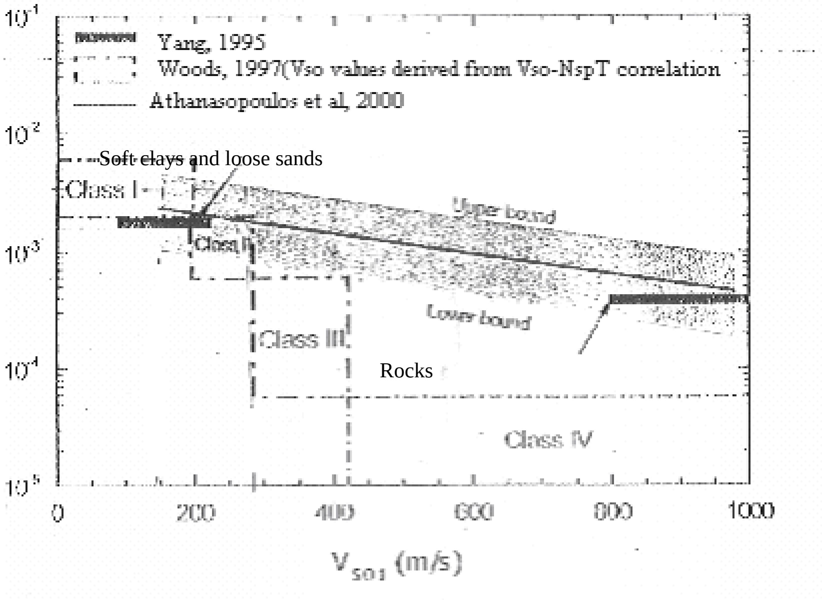


Fig.6.Range of a_0 values - results reported by other investigators

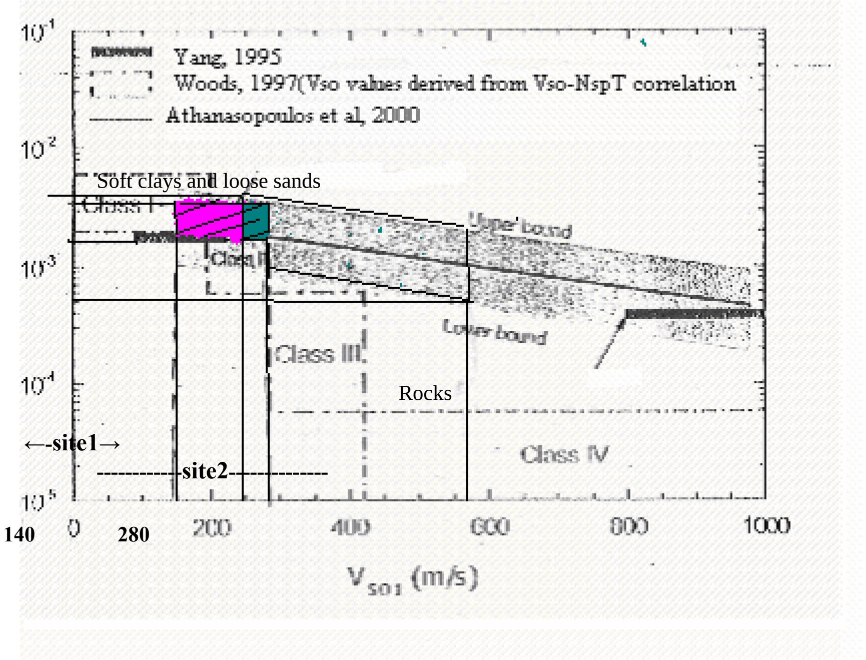


Fig.7. Range of a_0 values measured in the present study and comparison with results reported by other investigators – Site 1 is shown highlighted (hatched with color)