

# **DYNAMIC PROPERTIES OF DELHI SILT FROM FIELD INVESTIGATIONS**

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## **ABSTRACT**

All the earthquake resistant design and analysis procedures require site-specific/local dynamic site characterization. Dynamic site characterization includes shear wave velocity profile with depth, modulus reduction curves and damping characteristics of local soils. These are very essential and basic parameters required to conduct local site response/seismic wave propagation studies that should be duly incorporated into any earthquake resistant design/analysis.

Shear wave velocity profiling is not a routine Geotechnical investigation activity, as very specialized methods like seismic reflection, refraction, seismic cross-hole, down hole and steady state vibration tests which fall under the domain of geophysical methods, are required which are very time consuming and expensive. A rapid, inexpensive method of finding shear wave velocity profile at a site is Spectral Analysis of Surface Wave (SASW) method.

Results of SASW investigations conducted in Rohini, Delhi will be presented in the form of dispersion curves as well as shear wave velocity profile. Laboratory tests and field investigations (SPT, SCPT and DCPT) were also conducted on the same site and based on these results modulus reduction and damping versus strain curves were interpreted using the well established experimental results available in the literature. Further experimental studies and analysis of the collected data is required to corroborate these findings and give empirical correlations useful to practitioners. Efforts are underway in that direction.

## **INTRODUCTION**

Shear modulus and its variation with shearing strain are essential in characterizing soil behaviour during earthquake shaking. The need for accurate and economical measurement of this variable has increased greatly over the last decade, primarily due to the increased complexity of analytical procedures. One of the key elements in characterizing shear moduli in situ is measurement of shear wave velocity in the field at small strains (shearing strains less than 0.001 percent). The state-of-practice in such measurements employs seismic techniques such as the cross hole and down hole tests. However, these in situ tests are under-utilized because of economic, time and personnel considerations.

Spectral-Analysis-of-Surface-Waves (SASW) method is a relatively new seismic method for in situ measurement of low-amplitude shear wave velocities of soil deposits and thickness of soil layers. The SASW method is based upon generation and measurement of surface waves known as Rayleigh waves. The method is faster, economical, non-destructive and requires no boreholes (Hanumantha Rao, 2002). In addition, the method has the potential of nearly full automation- thereby virtually eliminating the need for specialized personnel to perform the test and analyse the data.

## **SITE PROFILE**

Extensive Geotechnical field investigations were carried out at the site in Rohini by Cengrs Geotechnica Pvt. Ltd (2002). Over 48 boreholes were drilled, 8 SCPT's and 32 DCPT's were conducted over an area of 30 hectares. The site was divided into four adjacent pockets. The borehole records of one of these pockets, which was selected for our analysis, indicated that the soils are alluvial in nature and consist of clayey silt and sandy silt to about 3 to 6 m depth. A 2 to 9 m thick silty fine sand layer underlies this. Below about 10 to 13 m depth, clayey silt/sandy silt with a minor discontinuity silty fine sand layer is encountered up to a final explored depth of 25 m. SPT values range from 4 to 4.0 m depth and from 9 to 15 to about 10.0 m depth. After 10 m depth, they range from 22 to 38 to the final explored depth of 25 m with some higher values at different depths.

## **SASW METHODOLOGY**

An imaginary centreline for the receiver array is first selected. Two receivers are then placed on the ground surface at an equal distance apart from the centreline. Several vertical impulses are applied to the ground by means of a hammer, which are averaged together for greater accuracy. Heisy et al (1982) recommend that the optimum distance between the source and near receiver should be approximately equal to the distance between receivers.

After testing in one direction is completed, the receivers are kept in their original position, but the source is moved to the opposite side of the imaginary centreline, and the test is repeated. This is called 'reversing the profile'. By performing forward and reverse tests and by averaging the records from the

two directions, the effect of any internal phase in the monitoring and recording systems is minimized.

Ignacio et al. (1987) found that the receiver arrangement can significantly influence the dispersion curve, and hence, the resulting modulus profile. The spacing between receivers is usually doubled from one spacing to the next. In each case symmetry of the receivers about the imaginary centreline is maintained. This arrangement is known as Common Receivers Mid Point (CRMP) geometry (Nazarian et al, 1983) and is preferred because the area covered in the previous test is included in the subsequent test. Close receiver spacings are used to sample near-surface material. As the distance between receivers increases, deeper materials are sampled.

Different sources may be used for different receiver spacings. For close receiver spacings (2m or less) a small hammer (such as a claw hammer) capable of generating high frequencies (above 250 Hz) is used. As receiver spacing increases, heavier sources capable of generating lower frequencies are required. For the largest spacing of 24 m sledge hammer has been used. For this study, two types of geophones were used. Geophones with 4.5 Hz natural frequency were used for spacing up to 8 m and geophones with 1 Hz natural frequency were used for larger spacings.

The signal is initially recorded by the WinTFS software, which subsequently transforms it from the time domain into the frequency domain by the use of Fast Fourier Transformation (FTT), and displays the coherence function and phase spectra of cross power spectrum. The data so obtained is processed further using the WinSASW software to mask the frequencies where the coherence is low, plot the dispersion curves, and finally generate the appropriate theoretical curve and stiffness profile.

The coherence function is a quantitative means of assessing the quality of signals captured by the receivers and the degree of distortion from noise. Coherence has a value between zero and unity, with a value of unity representing perfect correlation between the signals. Phase information of the cross power spectrum represents the phase difference between the two receivers at each frequency based on a rotating vector concept. By knowing the distance between receivers and the phase shift for each frequency, Rayleigh wave velocity and wavelength for each frequency are calculated. With this information a dispersion curve is constructed. A dispersion curve is a plot of (apparent) Rayleigh wave velocity versus wavelength. By applying an inversion process, an analytical technique for reconstructing the profile from the dispersion curve, the actual shear wave velocity profile is developed from which the shear modulus profile is calculated and layer thicknesses are determined.

## **CONSTRUCTION OF DISPERSION CURVE**

Based on tests at several soil sites, Heisy et al (1982) recommend that any data point with a wavelength greater than three times or less than one-half the distance between receivers should not be used to construct dispersion curves. These filtering criteria (which are based on equipment resolution and near-source effects) are applied to the dispersion curve for each receiver

spacing. As the distance between geophones is doubled each time, dispersion curves from different tests overlap, and the final outcome consisting of overlapping dispersion curves is continuous.

Nazarian and Stokoe (1986) recommended a threshold value of 0.9 for the coherence function. Based on this, we masked out a portion of the excited frequencies that failed to satisfy this recommendation. Furthermore, phase data with coherence values of more than 0.9, but having a phase difference of less than 120 degrees were also masked out, as recommended by Nazarian and Stokoe (1987) and Sheu et al. (1987). The final result of such an enhancement procedure, when applied to the averaged (forward and reverse) spectra for 16 m spacing, is illustrated in Fig. 1.

For each frequency (f) in the selected range, the phase difference ( $\Phi$ ) is determined, and the travel time between receivers (t) is calculated by:

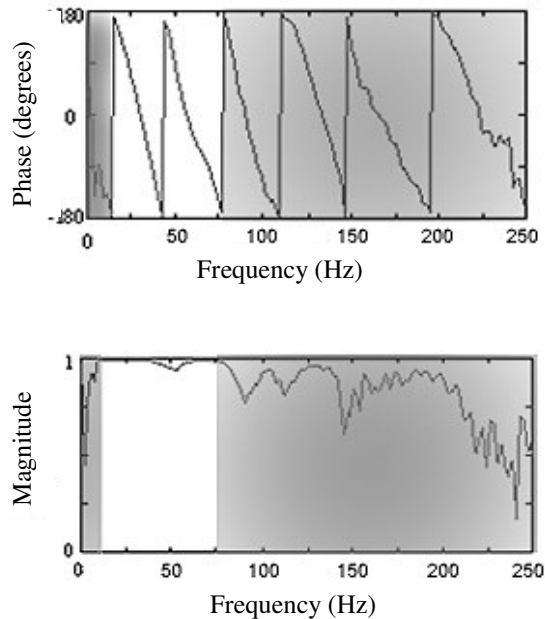


Fig.1. Phase and Coherence Spectra

$$t = (\Phi.T) / 360$$

where the period (T) is the reciprocal of the frequency. Because the distance receivers (X) is a known variable, Rayleigh wave velocity ( $V_R$ ) at each frequency is simply calculated by:

$$V_R = X / t$$

and the corresponding Rayleigh wavelength ( $L_R$ ) is calculated from

$$L_R = V_R / f$$

Rayleigh wave velocity corresponding to each wavelength is calculated. Based upon the experimental investigation data, Rix (1988) concluded that most of the surface wave energy is typically associated with the fundamental mode of vibration. According to this, the dispersion curve corresponding to 16 m receiver spacing, as shown in Fig. 2, can be concluded as belonging to a higher mode of vibration.

### INVERSION OF DISPERSION CURVE

Inversion of the dispersion curve is the process of determining actual propagation velocities (especially shear wave velocities) from the dispersion curve. The simplest way of obtaining the shear wave velocity profile using the dispersion curve is to assume that shear wave velocity is approximately equal to 110 percent of Rayleigh wave velocity and the depth of sampling is equal to 0.50 to 0.33 of the wavelength (Heisy et al. 1982, Nazarian et al. 1983).

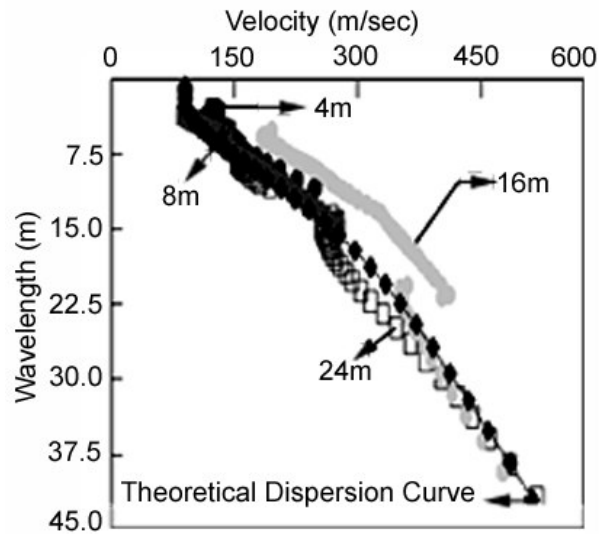


Fig.2. Experimental and Theoretical Dispersion Curves

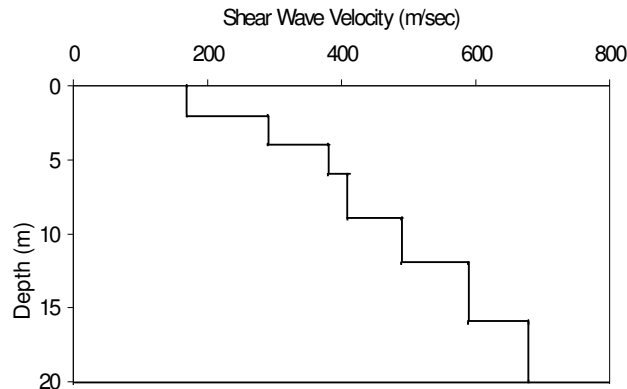


Fig. 3. Shear Wave Velocity Profile

The profile is divided into several layers. For a soil site, uniform layer thicknesses are normally assumed. A shear wave velocity profile is then selected as a first guess for each layer, and a theoretical dispersion curve is obtained from the WinSASW software. The software uses an algorithm developed by Hossain and Drenvich (1989). The theoretical and experimental curves are compared, and shown in Fig 2. If the two curves match within a reasonable tolerance the shear wave velocity profile is obtained. Otherwise, assumed shear wave velocities are changed, and the theoretical dispersion curve is recalculated. This trial and error process continues until the experimental and theoretical curves match reasonably well.

In this process the mass density and Poisson`s ratios of different layers are assumed. However, the effect of these parameters on the final outcome is small (Grant and West, 1965), especially for Geotechnical engineering projects in which Poisson`s ratio and mass density of different materials fall into fairly narrow ranges. The final shear wave velocity profile is shown in Fig.3.

**MODULUS REDUCTION AND DAMPING RATIO CURVES**

Vucetic and Dobry (1991), building on the work of Kokoshu (1980) in an investigation motivated by the performance of Mexico City clay in the 1985 Michoacan earthquake, showed clearly how modulus and damping behaviour are influenced by soil plasticity. Vucetic and Dobry developed families of modulus reduction and damping curves as functions of plasticity index. The curve for the selected PI is obtained by linear interpolation of the curves published by them. The modulus ratio ( $G/G_{max}$ ) versus Shear Strain ( $\gamma$ ) and Damping Ratio versus Shear Strain ( $\gamma$ ) curves (Figs. 4 and 5) corresponding to a Plasticity Index of 14, as indicated by the soil investigation report of the site averaged over depth, were interpolated using the Vucetic and Dobry curves and are shown bold with arrow.

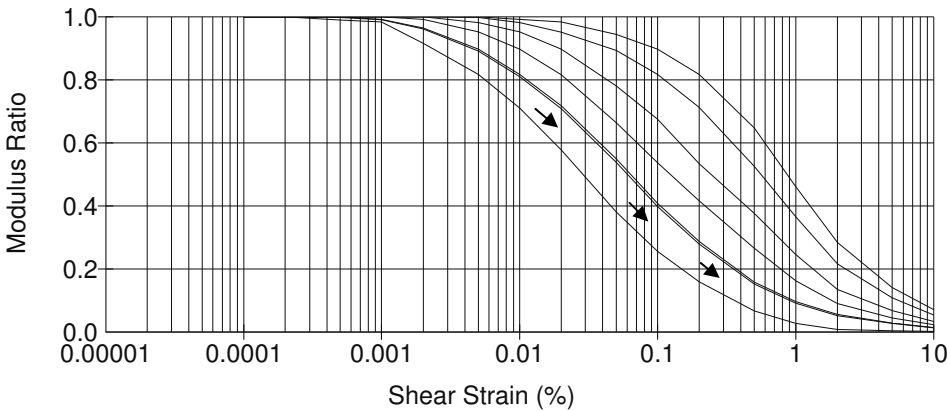


Fig.4. Modulus Reduction Curve

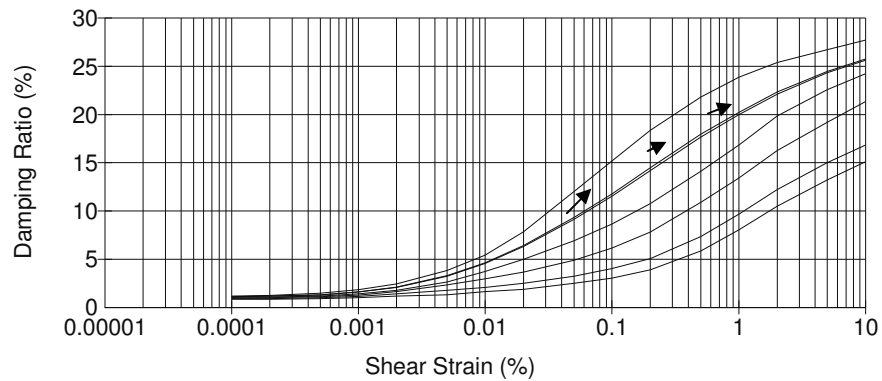


Fig 5. Damping Ratio Vs. Shear Strain

## RESULTS AND FUTURE WORK

Several SASW tests (over 30) were conducted at the Rohini site, and only a typical result has been illustrated in this paper. The detailed investigation of the collected data is currently in progress. With a plenty of SPT values with depth also being available at this site (48 bore holes with  $N$  values measured up to 25 m depth), it provides an excellent opportunity to develop an empirical correlation between measured  $N$  values and  $V_s$  with depth. The work is in progress along these lines. These empirical correlations will be of great help to designers and practitioners as stated earlier measurement of shear wave velocity with depth is still in its infancy in our country.

It is further planned to accumulate a large depository of SASW and SPT results, and employ a comprehensive statistical analysis to derive an empirical correlation between  $N$  value and shear wave velocity profile.

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