Measurements of Dynamic Properties and Soil Profiling Using Multichannel Analysis of Surface Waves

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ABSTRACT

Measurements of dynamic properties of subsurface, soil fill and embankments are very essential part in design of structures, roads, bridges, slopes and earthen dams for dynamic loading. Multichannel analysis of surface waves (MASW) is globally used method to measure the dynamic properties of subsurface materials and asses the quality of the sub grade, fillings, embankments, etc. MASW is a seismic wave propagation 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 consist of 24 channels Geode seismograph with 24 geophones of 4.5 Hz capacity, sledge hammer with switch, hammer plate and supporting software. The captured Rayleigh wave through geophones created by dynamic loading is processed to using SurfSeis software package to arrive the dynamic properties and soil profiling of surveyed location. SurfSeis is designed to generate Vs data of either 1-D or 2-D format using a simple three-step procedure: preparation of a Multichannel record (sometimes called a shot gather or a field file), dispersion-curve analysis, and inversion. In this paper, measurement of dynamic properties and soil profiling using MASW and some case studies are presented. MASW can be further used to study the behavior of soil, embankments and slopes due to passive source of loading such as load due to moving of train or vehicles, etc.

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1. Introduction

Geophysical technique of MASW is increasing being applied to geotechnical engineering for the measurements of dynamic properties, soil profiling, microzonation, and site response studies. In particular the MASW widely used in geotechnical engineering for the measurement of shear wave velocity, identification of material properties, martial boundaries and special variations of ground etc. Another advantage of MASW is non-intrusive and less time consuming. Multichannel analysis of surface waves is a seismic method that can be used for geotechnical characterization of near surface materials (Park et. al, 1999a; Xia et. al, 1999; Miller et. al, 1999). MASW identifies the each type of seismic waves on a multichannel record based on the normal pattern recognition technique that has been used in oil exploration for several decades. The identification leads to an optimum field configuration that assures the highest signal-to-noise ratio (S/N) ever possible. Effectiveness in signal analysis is then further enhanced due to the diversity and flexibility in the data processing step (Ivanov et. al, 2000). The MASW also generate the 2D shear wave velocity profile fast manner. The objective of this paper is to map the soil and rock layers, finding the dynamic properties site material and soil proofing. The measured dynamic properties (G_{max}) can be used for design of structures for earthquake/ cyclic loading, site response studies, settlement analysis and also Vs is widely used in liquefaction assessment.

2. MULTICHANNEL ANALYSIS OF SURFACE WAVES

The Multichannel analysis of surface waves (MASW) method is a nondestructive seismic method to evaluate material layer thickness, their shear wave velocity (1D (depth) or 2-D (depth and surface location)), passion ratio and density. This method is wide applied for measurement of dynamic properties, soil proofing, mapping of rock layer and evaluate pavement thickness, elastic modulus of ground and material under the pavement. The MASW has three unique advantages, first the field survey is easiest because of the strong nature of surface-wave energy that can be generated by using a simple impact source (e.g., a sledgehammer) and by following simple field logistics. Second, the data-processing step is usually so simple that it reliable determination of optimum processing parameters. This also indicates the potential for full automation of the entire processing step. Third, surface waves respond most effectively to various types of near-surface anomalies that are common targets of geotechnical investigation (Park et.al. 1999). The

MASW takes a full account of complicated nature of seismic waves that always contain harmful noise waves such as higher mode of surface waves, body waves scattered waves, traffic waves, etc. The components of MASW are shown in the Figure 1. MASW consist of 24 channels Geode seismograph with 24 geophones of 4.5 Hz capacities were used for the investigation. The captured Rayleigh wave is analyzed using SurfSeis software package. SurfSeis is designed to generate Vs data (either in 1-D or 2-D format) using a simple three-step procedure: i) preparation of a Multichannel record (sometimes called a shot gather or a field file), ii) dispersion-curve analysis, and iii) inversion (See Figure 2).

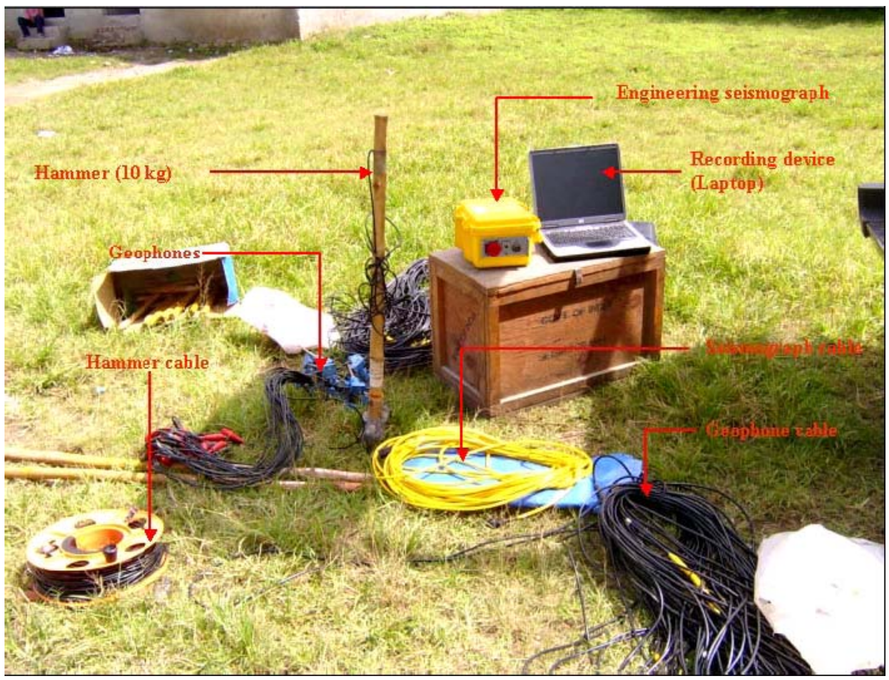

Figure 1: Components of MASW

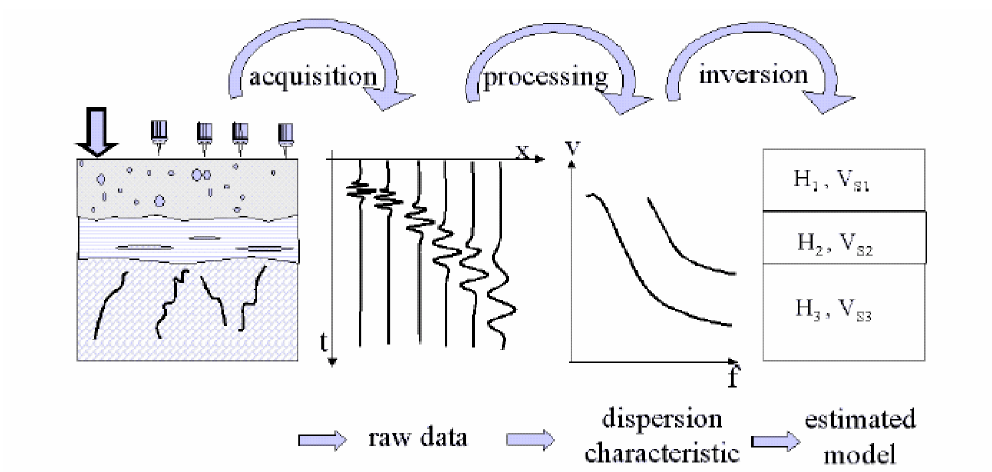

Figure 2: Scheme of Three-Step Method

2.1 Data Acquisition

A multiple number of receivers (24 geophones) are deployed with even spacing along a linear survey line with receivers connected to a multichannel recoding device of Geode (see Figure 3). Each channel is dedicated to recording vibrations from one receiver. One multichannel record (commonly called a shot gather) consists of a multiple number of time series (called traces) from all the receivers in an ordered manner.

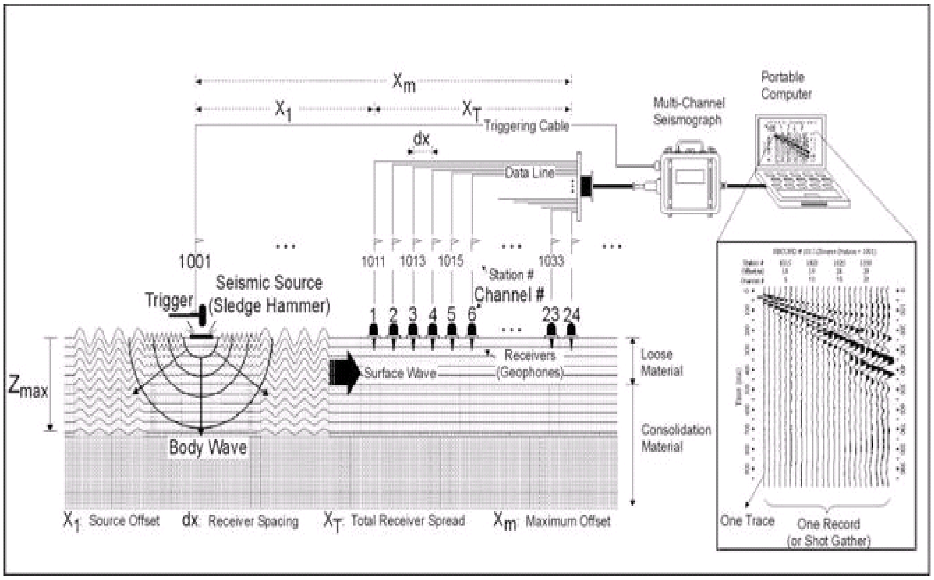

Figure 3: Schematic illustrating Multichannel Analysis of Surface Waves Survey

A swept source (a vibrator) or impulsive sources (a sledgehammer) are used to generate surface waves. For swept sources, raw uncorrelated data are optimum for multichannel analysis. Impulsive source data needs to be decomposed into the swept-frequency format to appropriately expose the phase velocity-frequency relationship of dispersive surface waves. The basic field configuration and acquisition routine for MASW is the same as that used in conventional CMP body-wave reflection surveys. Even with the dominance of surface waves on seismic data, effectively recording surface waves requires field configurations and acquisition parameters be favorable to the recording of planar, fundamental mode Rayleigh waves and unfavorable to all other types of acoustic waves. The source to the first receiver (offset X_1) must be large enough to ensure the Rayleigh wave is behaving as a horizontally raveling plane wave. Plane wave propagation of surface waves does not occur in most cases until surface waves have traveled a certain distance, called the near-offset (X_1), which is greater than half the maximum desired

$$x \geq 0.5\lambda_{\max} \quad (1)$$

wavelength (λ_{max}) (Stokoe et al., 1994). Different investigators have reported different optimum ratios between X_1 and λ_{max} (Stokoe et al., 1994; Gucunski and Woods, 1991). The normally accepted axiom is that penetration depth (z_λ) of surface waves is approximately equal to its wavelength (λ) (Richart et al., 1970), while the maximum depth (z_{max}) for which Vs can be reasonably calculated is about half the longest wavelength (λ_{max}) measured (Rix and Leipski, 1991). Rewriting equation (1) to represent maximum image able depths provides a good rule of thumb. Near-offset distances selected based on this thumb rule of equation 2.

$$x_1 \geq z_{\max} \qquad (2)$$

2.2 MASW—DISPERSION CURVE

The Recorded data (Raw data shown in Figure 4) need to be formatted in KGS format then dispersion curve has been prepared. The dispersion curve (DC) is the plot of phase velocity vs. frequency of the material. The generation of a dispersion curve is a critical step in all surface wave methods. Phase velocity can be calculated from the linear slope of each component on the swept-frequency record. A frequency-domain approach has been used to (Park et al., 1998b; 1999) to calculate the dispersion curve from on impulsive data. A typical dispersion curve obtained for Bangalore soil shown in Figure 5.

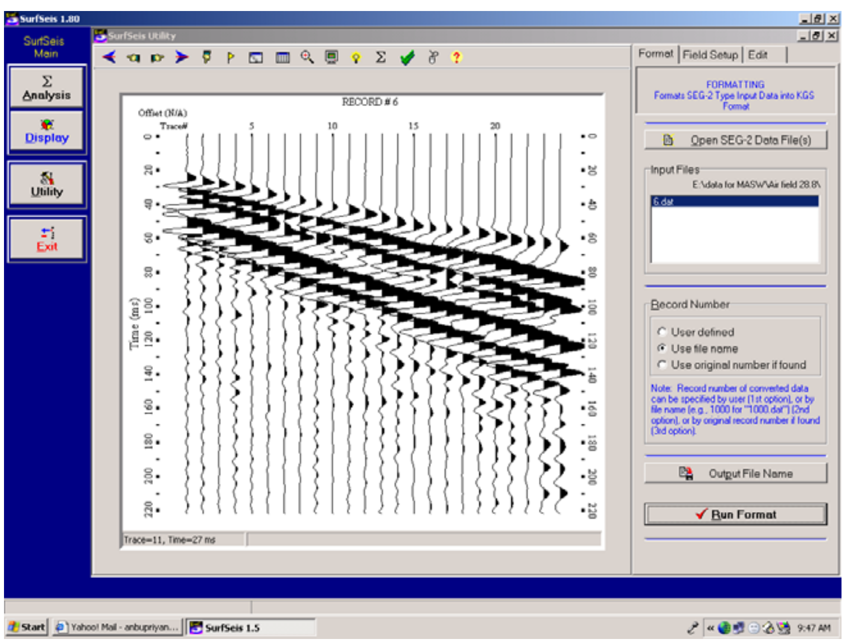

Figure 4: Typical Recorded (Raw) data in MASW

Figure 5 shows the frequency of range for soil (6 Hz to 14Hz) and phase velocity Range of soil (150m/sec to 500m/sec) in Bangalore.

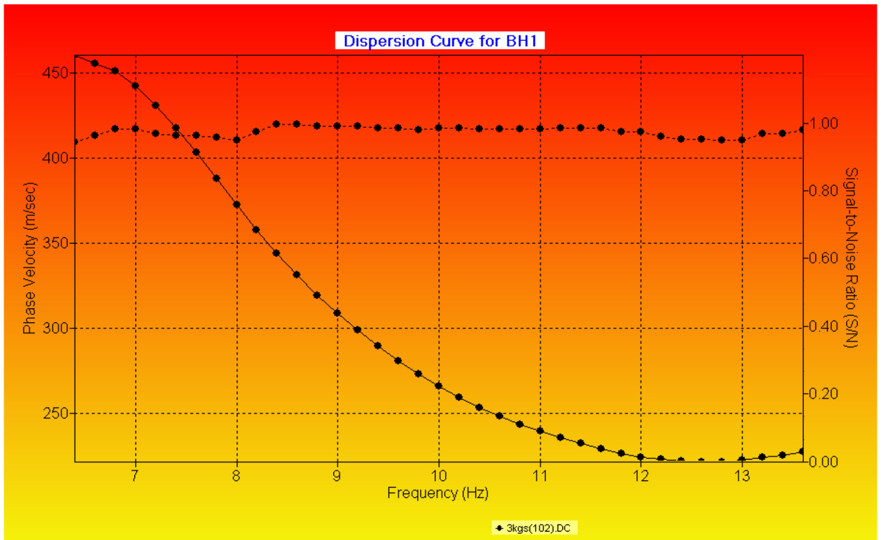

Figure 5: Typical Dispersion curve for Bangalore soil

2.3 MASW—INVERSION

The dispersion curve obtained form record desires the quality of results and depth of information of subsurface materials. Usually the decrease trend of DC is indicates that density material (Hardness) increase with depth, lower frequency of dispersion curve gives the greater depth of information. A Vs profile is calculated using an iterative inversion process requiring the dispersion data as input. A least-squares approach allows automation of the process (Xia et al., 1999). For the method employed here, only Vs is updated after 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. Among these four parameters, Vs has the most significant effect on the convergence of the algorithm. Several methods are reported to ensure convergence after calculating the initial Vs profile (Heukelom and Foster, 1960; Vardonlakis and Vrettos, 1988). An initial Vs profile is defined here by making the simple assumption that Vs at a depth z_f is 1.09 times (Stokoe et al., 1994). A typical inversion process in SurfSeis is shown in Figure 6 for Bangalore soil.

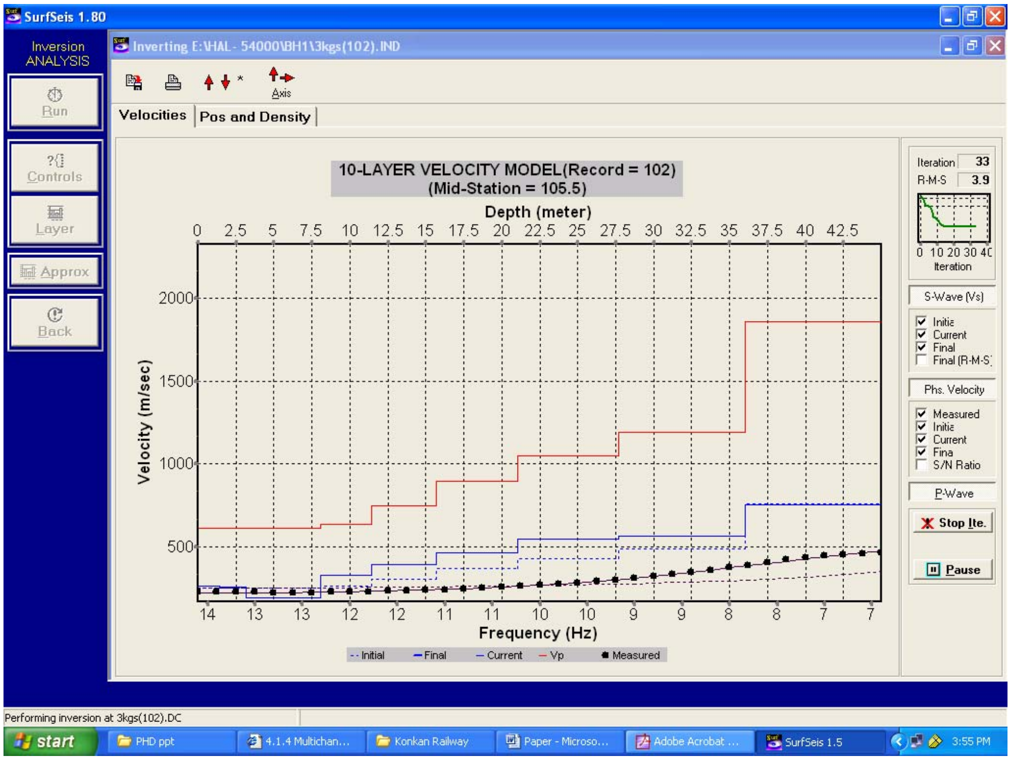

Figure 6: Typical Inversion Process

3. CASE STUDIES

Many researchers have addressed this issue around the world. At Indian institute of Science, Bangalore, the MASW testing has been carried out for many projects t determine the dynamic properties of the ground (particularly Gmax) and some of the test carried out and the results are summarized in this section. The typical case studies of measurement of dynamic properties and soil profiling are discussed and presented.

3.1 Measurement of Dynamic Properties

Dynamic properties of soils can be measured from in-situ as well as laboratory tests. The Field or in-situ tests have the advantage that the state of stress is inherently included in the procedure. However, laboratory tests need to confine and consolidate the soil sample back to the state of stress to replicate field conditions. Also getting undisturbed samples for loose soils is almost impossible and the in-situ structure of the soil gets disturbed in lab tests. A very important dynamic property (Vs, V_{S30} and G_{max}) of geotechnical material has been evaluated using MASW survey. The 1D-MASW and 2D-MASW test have been carried at many locations in Bangalore, Hyderabad and Delhi, dynamic properties are measured. In particular as part of microzonation project, at 55 locations in different part of Bangalore MASW survey has been carried out to delineate the subsurface features. The survey points have been selected such a way that the results represent the soil characteristics of the entire site. The shear wave velocities at low strain along each survey line are evaluated based on dispersion curve, which is shown in Figure 7. The description of each layer has been obtained based on shear wave velocity for each layers as per NEHRP classification of site categories (Martin, 1994) and IBC code site classification (IBC-2000). Figure 7 shows that the shear wave velocity varies from 150m/sec to 550m/sec, compressional wave velocity varies from 550m/sec to 1450m/sec up to depth of 50m from the ground level (GL). The dense soil/ weathered rock (shear wave velocity more then 360m/sec) start form 12.5m from the GL. In this corresponding location the hard rock (shear wave velocity more then 720m/sec) not found up to depth of 50m. The dynamic properties at low strain along each survey line are evaluated based on shear velocity a profile is shown in Tables 1. From Table 1, the shear modulus varies from 43MN/m^2 to 218 MN/m^2 and Young's Modulus varies from 111 MN/m^2 to 523 MN/m^2 for Bangalore soil. In few locations measured dynamic properties are cross verification of using SPT bore logs, it is very clear that martial classified using MASW -Vs is matches well with martial found in while drilling bore holes. Further the relation between corrected "N" (N_{60}) to Vs, Vs^{30} and G_{max} has been generated for the Bangalore soils.

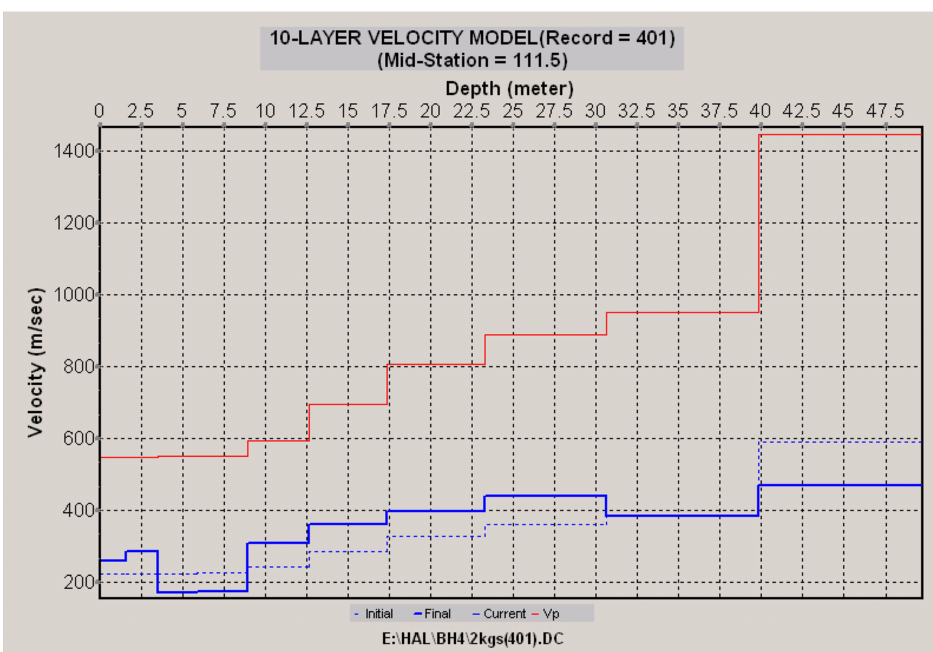

Figure 7: Compressional and shear wave velocity Plot Using MASW

Table 1: Dynamic properties of soil layers with depth using MASW system

Depth m	Vs m/sec	Density g/cc	Shear Modulus MN/m2	Poisson Ratio	Young's Modulus MN/m2
0-3.2	250	2.00	125	0.30	325
3.2-8.0	150	1.90	43	0.30	111
8.0-28.5	280	2.00	157	0.30	408
>28.5	330	2.00	218	0.20	523

3.2 Soil Profiling

In many geological setting, topographical variations and discontinuities in the subsurface, determination of nature and location of anomalous bedrock can be essential component of detailed investigation and identification of resources full materials (goal, ore, mineral deposit, etc). The soil proofing is identification of different martial and their thickness and spatial variation in the ground. The basic field configuration and acquisition routine for this application of MASW is the same as that used in 1D survey. That is, 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 one 1-D Vs profile in a manner previously stated. In this way a multiple number of Vs profiles are generated. The Vs data are then 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. A detailed survey has been carried out in the Delhi west to identify the spatial variation and thickness of the subsurface material. The soil profiles obtained from MASW is shown in Figure 8, the top layer consist of medium sandy soil having the velocity rage of about 250m/sec from 12m to 25.5m up to depth of 3.5m. The second layer consist of soft sandy silt found at depth of 3.5m to 10.5m up to 25.5m, beyond this it is found from surface. The dense soil found at depth of 10.5m to 30m with topographical variation as shown in the Figure 8. Very hard martial having the velocity of 600m/sec and above followed by the third layer. At depth

40m very soft martial found from 21.5m to 23m having the shear wave velocity of 250m/sec. Theses spatial variation also conformed by drilling of boreholes along the line.

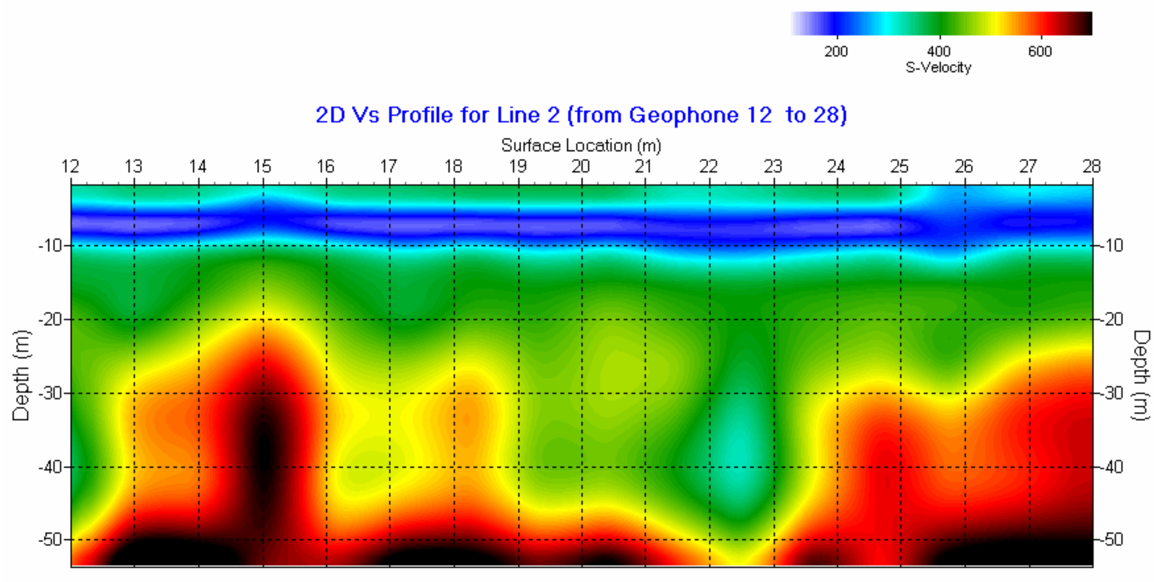

Figure 8: Soil Profiling Using MASW

3.3 Ground Anomalies

Many engineering construction progress was disrupted due to buried structures and unusual materials (Filled and debris material) found during the construction process. The MASW can be effectively used to identify the buried object and filled up materials in the site. A typical Vs profile of filled material site at Bangalore is shown in Figure 9. The site developed in the low laying area before 15 years by filling of waste materials. Recently they are planning to fix the sensitive earthquake measuring instrument below the depth of 18m from the GL. While drilling they used rotary drilling, they found that after 1.5m big stones are present in the site. We investigated the site using MASW, it very interesting that top surface (0.3 to 1m) good soil present, but below this lot of debris present unevenly which is shown in Figure 9. Figure 9 clearly shows very low shear wave velocity due the scattering of wave in the filled materials up to depth of 10m from surface. That area was water tank before 15years while construction of building; they filled using available material near by. Finally we recommended them to go for power drill so that the debris can be easy drilled. Recent developments in MASW also help to find the behavior of soil, embankments and slopes due to passive source of loading such as load due to moving of train or vehicles.

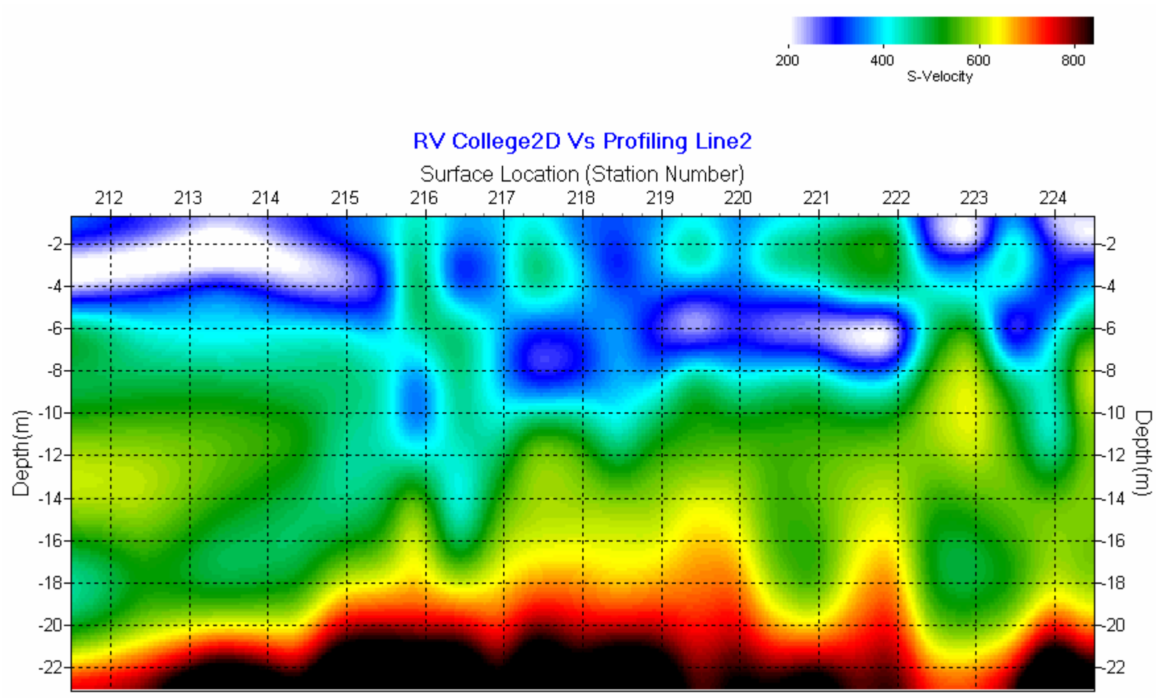

Figure 9: Ground Anomalies in the filled up soil

4. CONCLUSIONS

This paper presents the MASW system, surveying and application to the geotechnical engineering field. MASW can be used effectively to measure the shear wave velocities and calculation of dynamic properties of materials in the in-situ condition at low stain level. The spatial variation of materials, soil profiling, identifications and mapping of rock can be done with short time using MASW. This method can be further used to identify the buried objects and filled up materials in the construction site to select proper method and equipment for construction. This method is very popular as this is non destructive in nature and requires less time for testing. This method can be used in slopes, embankments and roads. The measured dynamic properties can be used for structural deign for cyclic / earthquake loading condition.

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