9th Biennial International Conference
& Exposition on Petroleum Geophysics

"HYDERABAD 2012"

P-320

MASW versus Refraction Seismic Method in terms of acquisition and processing of data and the accuracy of estimation of velocity profiles.

Aayush Kesarwani, Aditi Sharma*, Chirag Jain, *Indian School of Mines*

Summary

Near surface geophysical surveys commonly involve determination of seismic velocities and hence subsoil characterization. Refraction seismic methods have been conventionally used since times immemorial for mapping the velocity structure. Advances in geophysical survey techniques resulted in the emergence of Multi-Channel Analysis of Surface Waves (MASW) as one of the latest techniques used for shallow subsurface profiling. It is based upon the dispersive nature of surface waves. The sampling depth of a particular frequency component of surface waves is in direct proportion to its wavelength which makes the surface wave velocity frequency dependent, i.e. dispersive. The shear wave velocity structure can therefore be obtained by the inversion of surface-waves dispersion curve. A meticulous and comparative study of both these methods in terms of time-efficiency, accuracy of results, reliability, range of validity and cost factors reveal that MASW is a more universal method. The fact that it puts to use surface wave component of seismic waves and not body waves plays a vital role in giving it an upper-hand over refraction methods. Signal to noise ratio (S/N ratio) is maximized in MASW. Also refraction seismic methods require as a requisite condition that the earth under survey should be made up of layers of material that increase in seismic velocity with each successively deeper layer. This constraint again adds to the advantages of MASW which has no such limitations. Besides, refraction methods can give erroneous results when a low-velocity layer underlies a high-velocity layer. Hence MASW comes across as a powerful, accurate and cost- effective tool for imaging the subsurface and estimating accurate shear-wave velocity of structures

Introduction

The conventional seismic methods used for near-surface studies have been mostly either high-resolution reflection or refraction techniques. Near-surface investigations dominantly comprise characterization of the sub-surface medium as it is one of the most important steps in geotechnical engineering. Identification of the soil properties i.e. elastic and dissipative characteristics is crucial to various aspects of engineering such as site response evaluation, foundation of vibrating machines, earthquake engineering, etc.

The analysis of the propagation of seismic waves emerges as the most widely used fundamental principle in various different techniques employed for characterization of sub-soil. Compressional waves (P- waves) and shear waves (S-waves) are used for seismic reflection and refraction in vertical seismic profiling and seismic tomography. And the surface waves, often called the ground roll, are usually been considered as coherent noise masking useful signals and polluting the seismic record. Multi-Channel Analysis of Surface Waves (MASW) is such a technique which uses these surface waves for shallow subsurface profiling. MASW is the latest technique for mapping the subsurface which uses the dispersive nature of Rayleigh wave i.e. surface waves to obtain shear wave velocity structure.

Theory and Method

Seismic refraction technique involves the estimation of the P-wave acoustical velocity of the earth's near-surface soils to depths typically less than 100 feet. The underlying principle behind seismic refraction technique is the measurement of travel times of the seismic waves refracted at the interfaces between the subsurface layers of different velocities. The seismic energy generated by a seismic source ('shot') located on the surface radiates outward from the shot point spreading in all directions. It

Room No.215, Ruby Annex New Hostel, ISM Dhanbad-826004;
aditi.hi2u@gmail.com

may either travel directly through upper layer (direct arrivals), or it may travel down to and then laterally along the high velocity layers (refracted arrivals) before bouncing up and coming back to the surface. The data are recorded on a seismograph and travel-time versus distances curves are then drawn. These curves are utilized to calculate velocities of the overburden and refractor layers. Considering the shot and receiver geometry, the analysis of the measured travel-times and the calculated velocities gives the depth profiles for each refractor. The final output hence comprises a depth profile of the refractor layers and a velocity model of the subsurface. The primary applications of the seismic refraction technique are for determining the depth to bedrock and bedrock structure. And it is because of the dependence of seismic velocities on the elasticity and density of the material of the subsurface layer through which it is passing seismic refraction surveys also give a measure of material strengths. Consequently it acts as an aid in assessing rock strength and rock quality.

On the other hand, surface waves are seismic waves propagating parallel to the earth's surface without dissipating or spreading energy in the earth's interior. Rayleigh waves, the principal component of ground roll, are more widely used than Love waves as they permit a simpler acquisition.

These waves generated in all seismic surveys have the strongest energy (more than two-thirds of the total energy is carried by the ground roll) and hence Rayleigh waves appear as dominant events in seismic records. Their propagation in vertical direction in a vertically heterogeneous (i.e. layered) medium exhibits a dispersive behavior. By the term dispersion it implies that different frequencies have different phase velocities. Unlike in a homogeneous medium where all wavelengths have the same velocity on account of the same material everywhere, in a heterogeneous medium the surface waves exhibit differences in their behavior. There occurs an exponential decrease in their amplitude with depth and most of the energy propagates in a shallow zone (roughly the length of one wavelength). In a layered medium, the surface wave does not have a single velocity but a phase velocity that is function of the frequency. This relation between the frequency and the phase velocity is known as the dispersion curve. At higher frequency values the phase velocity is the Rayleigh velocity of uppermost layer of the medium whereas at lower frequency values the effect of deeper layers becomes more and more dominant with the result that the phase velocity tends asymptotically to Rayleigh velocity of the material in the deepest layer. This dispersive nature of Rayleigh waves is utilized in MASW to map the values of shear wave velocities (Vs) in the subsurface.

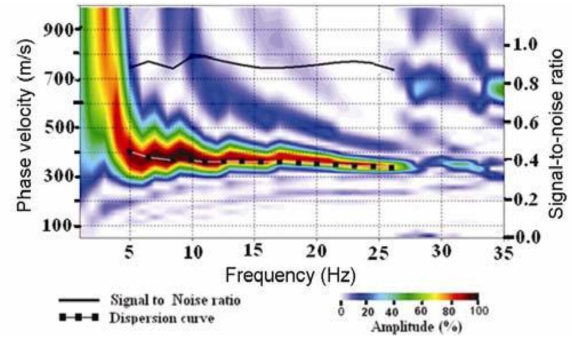

Figure 1: A typical Dispersion curve

Rayleigh-wave phase velocity (dispersion data) is actually a function of four parameters: (i) S-wave velocity, (ii) P-wave velocity, (iii) density, and (iv) layer thickness. Each parameter contributes to the dispersion curve in a unique way. Rayleigh-wave phase velocities are influenced much less by changes in P-wave velocities than by changes in density. A 25% increase in P-wave velocities represents a maximum difference of <20 m/s, or an average relative change of less than 3%. This significant change in P-wave velocity has a very subtle effect on the phase velocity. The effect of layer thicknesses on Rayleigh-wave phase velocities can be minimized by dividing the subsurface into thinner and thinner layers within each unique and constant S-wave interval velocity. Analysis have shown that the ratio of percentage change in the phase velocities to percentage change in the S-wave velocity, thickness of layer, density, or P-wave velocity is 1.56, 0.64, 0.4, or 0.13, respectively. The S-wave velocity is hence the dominant parameter influencing changes in Rayleigh-wave phase velocity.

Multi-Channel Analysis of Surface Waves (MASW) is a non-invasive method of estimating the shear-wave velocity profile from surface wave energy. It utilizes the dispersive properties of Rayleigh waves for imaging the subsurface layers. In active MASW method ground roll (surface waves) can be easily generated by a swept source like a vibrator or an impact source like a sledge hammer. The investigation depth is usually shallower than 30 m. The entire procedure for MASW consists of three steps: (a) acquiring multi-channel field records (or shot gathers); (b) extracting dispersion curves (one from each record); and (c) inverting these dispersion curves to obtain 1-D (depth) VS profiles (one profile from one curve). VS profiling can be done 1-D (depth) or 2-D (depth and surface location) format, thereby estimating the subsoil properties. The processing is done using SurfSeis software package to arrive at the dynamic properties and soil profiling of the 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 multi-channel record; dispersion curve analysis and inversion.

The term multi-channel record indicates a seismic dataset acquired using a recording instrument with multiple channels. In most cases the data is acquired using the standard CMP roll-along technique to achieve a continuous shot gather. When a seismic source, say a sledge hammer, generates seismic waves after regular intervals, these waves are recorded by 24 vertical geophones or receivers planted at a 2 m interval along the profile line. Such MASW tests are carried out at numerous different locations in the study area. The generation of dispersion curves is a very important step in MASW. Each dispersion curve is obtained for a corresponding location. The first step is to invert each dispersion curve into an x-Vs trace which represents the variation of shear wave velocity with depth at location x. Gathering all such x-Vs traces into a shot station in sequential order results in a 2-D grid of the shear wave velocity profile.

Care is taken to ensure that the spectral properties of the t – x (t is the time and x the offset) data (shot gathers) are consistent with the maximum and minimum f – Vc values (f is the frequency and Vc the phase velocity of surface waves) contained in the dispersion curve. Each dispersion curve is individually inverted into an x – Vs (z) trace (Vs (z) is shear-wave velocity variation with depth at location x). The shear-wave velocity is averaged and is computed using the formula:-

$$V_s30 = \frac{30}{\sum_{i=1,n} d_i / V_{si}}$$

Where d_i is the thickness of the i^{th} layer (in m), V_{si} is the shear-wave velocity in the i^{th} layer (in m/s) and shear wave velocities of N layers exist in the top 30 m.

Thus it is obvious by procedure as explained above that MASW comes across as a more efficient and accurate process for mapping the subsurface of an area. Refraction seismic method employs the use of body waves while MASW uses surface waves. In seismic surveys, when a P-wave source is used, more than two-thirds of the total seismic energy is imparted into Rayleigh waves (the principal component of ground roll). Also keeping in mind the fact that these waves occur as coherent noise arousing the requirement of their filtration from the data, the use of surface waves in imaging the near-surface appears more convincing and better.

Signal to noise ratio i.e. S/N ratio is a vital parameter and must be taken into account while deciding the technique, the choice of seismic source, and also while processing the recorded data. S/N ratio not only depends on local conditions but also on the strength of signals generated. Maximization of S/N ratio during acquisition and subsequent processing steps is necessary for the accuracy of the results and hence for the correct interpretation of the subsurface geology. Optimum field parameters such as receiver spacing, spread length of survey lines, etc. must be precisely determined so that the information up to the required depth is obtained with maximum S/N ratio. Multi-channel recording permits effective identification and isolation of noise as per distinctive trace-to-trace coherency in arrival times and amplitude. An added advantage is the speed and redundancy of the measurement process. Contamination by coherent noise hence adds to the demerits of the refraction seismic method. Also in noisy urban environment it is often difficult to generate signals strong enough to be effective. Again Rayleigh waves (that carry more than 2/3 of the energy generated) emerge as more convenient option for seismic surveys in such locations.

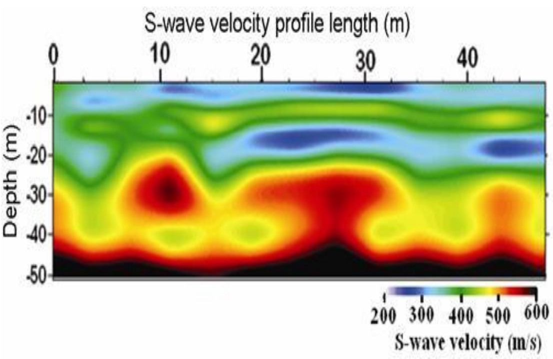

Figure 2: Typical 2-D velocity profile using MASW.

Site amplification is another important aspect for obtaining a good velocity curve. From seismological point of view, shear-wave velocity is the best indicator of a material's stiffness as it is directly related to shear modulus. Also apart from characterization of the ground type shear-wave velocity is a critical input parameter for any ground motion simulation and estimation of site amplification. On one hand where seismic refraction procedure requires to be conducted separately using longitudinal (P-waves) and shear (S-waves) waves using two sets of geophones (vertical and horizontal), thereby making it time-consuming, in MASW shear wave velocity is directly obtained by inversion of surface wave dispersion curve.

A close examination of the basic fundamental of the seismic refraction method reveals a big limitation to its validity and correctness of its results in near-surface studies. The seismic refraction method requires that the earth in the survey area be made up of layers of material that increase in seismic velocity with each successively deeper layer. The data analysis becomes more complicated and time-consuming if the layers dip or are discontinuous (which is mostly the case as the earth is not a perfect ideal parallel-layered model as assumed while studying refraction). The requirement for increasing velocity is a severe constraint in several shallow surveys where low-velocity layers are often encountered within a few meters or tens of meters below the earth's surface. For instance if a sand layer underlies a clay layer (sand has a lower velocity than clay) then the seismic refraction method in such a situation gives erroneous results and hence should not be used. Here gain we see that the seismic refraction fails when it comes to the range of validity and accuracy of results.

The seismic refraction is commonly performed either in areas where the geology is not complex or in places where the objective is to map the top of bedrock. Contrarily MASW is used to map soil and sediment thickness and elevation of subsurface interfaces such as the top of bedrock. MASW can be also used to determine shear wave velocity or density of subsurface material and the presence and location of voids and karst features.

Considering the relative simple and basic equipment of seismograph (for example 24 channels), seismic source (hammer striking a steel plate), and the MASW technique represents a rather elegant and versatile approach to shear wave data acquisition. Changes in the selection of a source, the number of geophones and the geophone interval can quickly be made in order to select the optimum field parameters for survey in a particular location. It should be mentioned here that the depth of investigation can be increased by using a dropping weight hammer and change in the shot intervals.

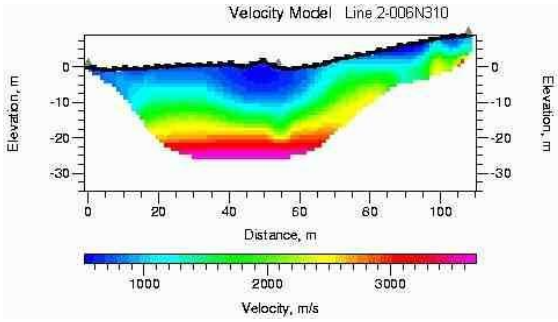

Figure 3: A typical velocity profile using Refraction Seismic Method.

The MASW method can be applied to seismic characterization of pavements, to study Poisson ratio, seismic study of sea-bottom sediments, mapping bedrock surface, and detecting dissolution features. Sinkholes and related subsidence features, obscured by suburban development and not detectable by using other geophysical methods because of power-line and mechanical noise, reinforced concrete, and non invasive testing requirements

Next talking about frequency range required. Body waves have higher frequencies than surface waves. Seismic refraction surveys consist of wavelets with frequencies higher than that of 50Hz. The multi-channel analysis of surface waves (MASW) method deals with surface waves in lower frequencies (usually 1-30Hz).

Conclusion

Thus we see that Multi-Channel Analysis of Surface Waves emerges as a better method as compared to the refraction seismic method for subsurface profiling because of the acute accuracy and enhanced efficiency of the results obtained. The MASW technique has in recent years gained in increasing popularity as this method is a powerful, rapid and cost-effective tool for estimating accurate shear wave-velocities of the structures beneath the earth. It has emerged as a quick and reliable method for the purpose of site characterization which assumes primary importance in earthquake engineering.

References

Park, B. Choon, Miller, D. Richard, and Xia. Jianghai, 1999, Geophysics, Vol. 64, No. 3, Multichannel analysis of surface waves.

Ricerca, Di Dottorato, Geoingegneria Ambientale POLITECNICO DI TORINO, Extract from PhD Thesis - Claudio Strobbia, Surface Wave Methods : Acquisition, processing and inversion.

Sairam, B., 2011, Seismic site characterization using Vs30 and site amplification in Gandhinagar region, Gujarat, India.

Acknowledgements

We extend our sincere thanks to B.Sairam (Scientist, Institute of Seismological Research, Gandhinagar, and Gujarat) for his fruitful guidance and supervision that proved instrumental in successful completion of this work.