Integration of Downhole Data Reduction Techniques for Determination of V_S Profiles

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ABSTRACT

The downhole method is one of the most widely used in situ seismic tests to determine shear wave velocity (V_S) profiles for site characterization and site response analysis. Although easy to perform in the field, it has always been a tedious task to accurately interpret the downhole data based on the arrival times of shear waves at the borehole receiver. Commonly used methods are the direct, interval, and Snell's Raypath methods. Snell's Raypath method has been known to provide the best results for downhole processing at multilayered subsurface sites as it considers the actual travel path of waves considering the refraction along the wave travel path. The direct method is considered better when the soil layers are uniform with reduced chances of refraction. In this study, V_S profiles are estimated for two boreholes 100 m deep at a deep silty deposit underlain by sandstone rocks. The Snell's Raypath method was observed to be more suitable for shallow subsurface to capture a greater variation in properties and need for a higher resolution in shallow subsurface. The direct method was found suitable for deeper layers where dense soil and rock layers are located, which show more uniform layering with depth.

INTRODUCTION

Shear wave velocity (V_S) is the key parameter in the site response analysis or seismic site characterization. It is one of the most useful engineering properties of soil and rock because of its direct relationship with the shear modulus of the material. Thus, V_S profiling is an important parameter for major engineering studies. These profiles are measured in the field using seismic methods. The depth of investigation generally varies between 30 to 150 m. However, deeper profiling up to 500 – 600 m has also been carried out recently (Stokoe et al. 2017, Hwang et al. 2018). There have been several methods developed to interpret the downhole data and estimate accurate V_S profiles. However, there is uncertainty over the applicability of these methods because these all methods determine V_S profiles in different ways. There is no consensus on using these methods in an integrated manner to obtain reliable profiles as each method has its own benefits and shortcomings. The widely followed test standard D7400 – 2019 suggests the use of direct and interval methods, which are applicable when refraction in subsurface can be neglected or is expected to be minimum. Thus, in this paper, an attempt has been made to understand differences in profile obtained from two commonly used interpretation methods and combine them together. The major objective is to highlight the importance of an integrated approach in downhole data interpretation. In this study, the downhole method commonly used to measure V_S is described. Methods used for interpretation of arrival time of generated waves and processing of those arrival times for calculation of V_S are discussed. Finally, downhole seismic tests were carried out at two locations in the East Indian Coastal region and compared with borehole profile and MASW results performed at the same location.

DOWNHOLE TEST

The downhole test is widely used for the in-situ determination of shear (S-) and compressional (P-) wave velocities of soil and rocks. The downhole method estimates the velocity of body waves in different subsurface layers by measuring the arrival time of waves from the source on the surface to the receiver/s at different depths in one borehole. The downhole test is economical because of a single borehole, easy procedure, and use of surface source as simple as a sledgehammer and a wooden plank. Another added advantage is that samples are obtained during drilling, which can later be used for a detailed study of soil and rock properties.

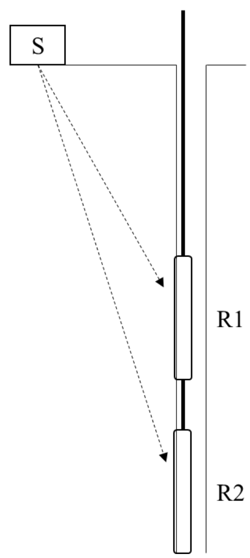

Figure 1. Schematic of a typical downhole test showing surface source and two receiver positions in the borehole

The schematic of the test is shown in Figure 1. The test consists of an impulsive or vibratory source for the generation of P- and S-waves on the surface. A static load is placed over the source to ensure firm contact between the source and the ground. A 3- (or more) channel receiver is placed in the borehole with a clamping mechanism to have firm contact with the borehole lining. After each acquisition, the receiver is progressed to the next recording depth. The acquisition interval can be 1 m or 1.5 m or can be decided based on the total depth of the borehole as well. For detection of the arrival of S-waves, polarity reversal of S-waves (when the sledgehammer hits the shear beam on the opposite sides, or the vibration source is excited in two opposite directions) is employed. This is discussed in the next section.

Data Processing. For the determination of V_S profiles, arrival times of body waves should be determined first. To determine the arrival time of an S-wave at a specific depth, reverse polarised S-waves are used, as shown in Figure 2. This method is termed as crossover method. It is a general observation that S-waves show a change in polarity when the excitation direction of the source is reversed. The section of wave signal before the arrival of the S-wave is mostly P-wave, which does not show polarity reversal. So, S-waves can be clearly identified. Hence, this technique is utilized. After the arrival time of the wave at all the depths is obtained, data reduction techniques are applied, as discussed below.

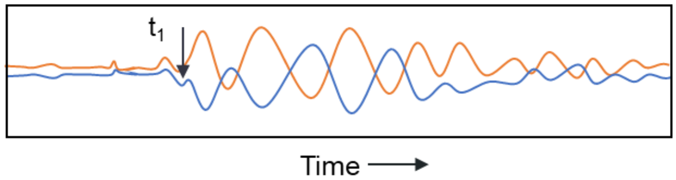

Figure 2. Detection of S-wave arrival time (t_1) by Crossover method

Direct Method. The direct method considers a straight travel path from the source to the receiver. This method can be useful when the source distance is sufficiently small compared to the depth of acquisition and refraction because the multi-layer soil profile can be neglected. For processing, first, the measured travel time in the inclined ray path is corrected to the vertical travel time as in Eq. 1 (Mok 1987, Batsila 1995, Kim et al. 2004).

$$t_c = D\frac{t}{R} \tag{1}$$

where, t_c= Vertical (or Corrected for Vertical) arrival time, D = depth of acquisition, R = source-receiver distance.

After plotting t_c vs. D, the velocity of each layer can be found by measuring the slope of straight lines which best fit these points in their respective layers.

Interval Method. The Interval method uses the difference in travel time of waves between two depths of acquisition. The wave velocity is given by Eq. 2 (Batsila 1995; Mok 1987, Kim et al. 2001).

$$V = \frac{R_2 - R_1}{t_2 - t_1} \tag{2}$$

where, R_1= source-receiver distance for depth of acquisition R_2= source-receiver distance for lower depth of acquisition, t_1= travel time for upper depth, t_2= travel time for lower depth.

The Interval method is simple to use. However, it does not consider the velocities of all the layers along the ray path and fails when $t_2 < t_1$, i.e., travel time to the lower depth is lower than the travel time to the upper depth. This can occur in profiles with high velocity contrast.

Snell's Raypath Method. The previous two methods considered a straight line, inclined travel path between source and receiver. To overcome this limitation, computations considering Snell's Law along the travel path were developed, resulting in Snell's Refracted Raypath method (Joh and Mok 1998, Bang 2001). This method assumes a refracted ray path based on Snell's Law between the subsurface layers (Figure 3). For the first layer, V_1 can be calculated directly based on straight raypath length and arrival time as the uniform layer is assumed. Based on the travel time and source-receiver geometry for the subsequent layers, the following equations are solved to calculate velocity (Kim et al. 2004).

$$\text{Snell's Law: } \frac{\sin\theta_{i,1}}{V_1} = \frac{\sin\theta_{i,2}}{V_2} = \cdots = \frac{\sin\theta_{i,j}}{V_j} = \frac{\sin\theta_{i,i}}{V_i} \tag{3}$$

$$Z_1 \tan\theta_{i,1} + Z_2 \tan\theta_{i,2} + \cdots + Z_j \tan\theta_{i,j} + \cdots + Z_i \tan\theta_{i,i} = S \tag{4}$$

$$L_{i,j} = \frac{Z_j}{\cos\theta_{i,j}} \tag{5}$$

Then, velocity can be calculated as

$$V_i = \frac{L_{i,i}}{t_{i,i}} = \frac{\frac{Z_i}{\cos\theta_{i,i}}}{t_i - \sum_1^{i-1}\frac{L_{i,j}}{V_j}} \tag{6}$$

where, $L_{i,j}$ = Length of travel path for i^{th} receiver in j^{th} layer, $t_{i,j}$ = Time of travel along ray path for the i^{th} receiver in the j^{th} layer, $\theta_{i,j}$ = Angle with normal for i_{th} receiver's ray path in j^{th} layer

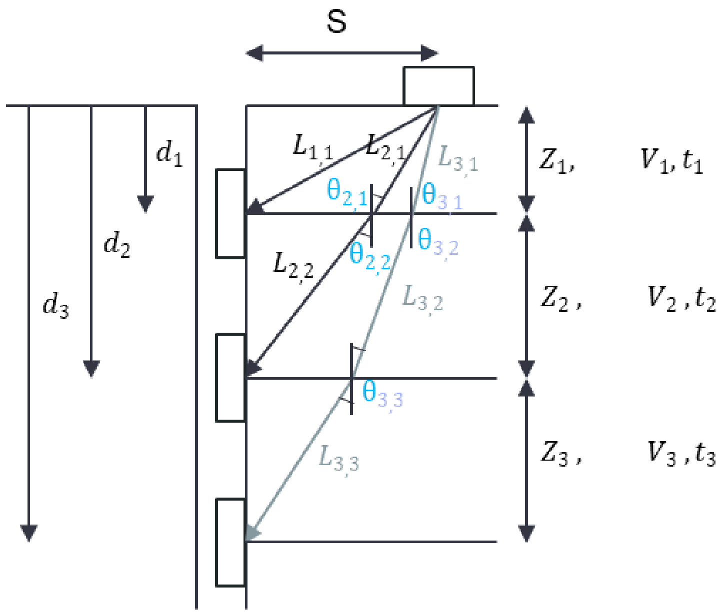

Figure 3. Illustration of Snell's Raypath Method for a three-layer model (after Kim et al. 2004)

To start with these equations, First an initial value of V_i needs to be assumed, which can be the average velocity given by $V_i = {}^{R_i}/_{t_i}$(R_i is the straight line distance between source and receiver at concerned depth, t_i is the arrival time at concerned depth). These equations are solved by iteration. V_i is updated after every iteration. The iteration is continued till the difference between the assumed and the calculated velocity at the step reduces below the defined lower limit (e.g., 0.01%) (Kim et al., 2004). In the present study, the calculations were performed using MATLAB 2021a software package.

It has been observed that these different methods result in different V_S profiles which often do not agree with subsurface layering. In order to understand the differences obtained due to application of these different methods, and how to integrate them to utilize the advantages provided, an integrated approach is proposed in this study.

FIELD STUDY AND DATA ACQUISITION

This study is carried out near the eastern coast of India over a silty deposit underlain by sedimentary rock layers. Two boreholes up to a depth of 100 m were drilled using hydraulic rotary drilling equipment accompanied by the Standard Penetration Test (SPT) for sample collection and general characterization of the subsurface. The boreholes were then prepared for the downhole test as per ASTM 7400 – 2019. The downhole test setup included a wooden shear beam with steel caps at the ends, a sledgehammer to generate an impulse, and a metal plate for vertical impulses. The beam was kept at a distance of 2.5 m from the borehole. The impulses were given in opposite directions to reverse the S-wave's polarity to easily identify its arrival. Geode Seismograph (Geometrics) was used for data acquisition along with a BGK7 borehole receiver (Geotomographie GmBH). Impulses were recorded at every 1 m depth interval.

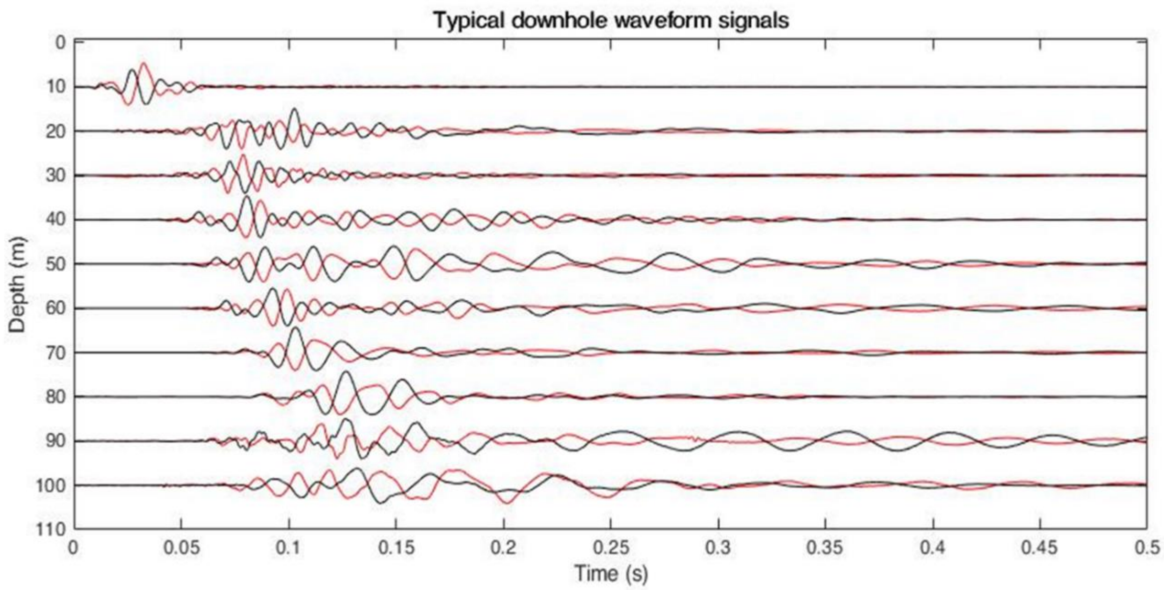

Figure 4. Typical S-wave signal traces at 10m depth intervals at site DH 2

MASW tests were carried out at both the test location using Geode seismograph and 24 nos. 2Hz geophones. A sledgehammer and a metal plate were used as source. Geophone interval was kept as 1m and source was placed at 10m from the nearest geophone. The V_S profile was determined considering a 10-layer subsurface model.

RESULTS

Before arrival time detection, a low pass filter of 100 Hz was applied to remove the noise from the wave records. Then, both the direct method and Snell's Raypath method were used for processing S-wave arrival times. A typical waterfall plot of the acquired waveforms at 10m intervals at the DH 2 site is shown in Figure 4. Vertical arrival times (t_c) are plotted against depth for both the boreholes in Figure 5(b) and Figure 6(b). Firstly, the direct method is used to estimate the V_S. The direct method was observed to miss a detailed profile for shallow depth where variability in soil properties is known beforehand from borehole drilling and soil sampling. Hence, Snell's Law Raypath is carried out for shallow depth to assess the soil stiffness with a better resolution and later integrated with the V_S profile from the direct method.

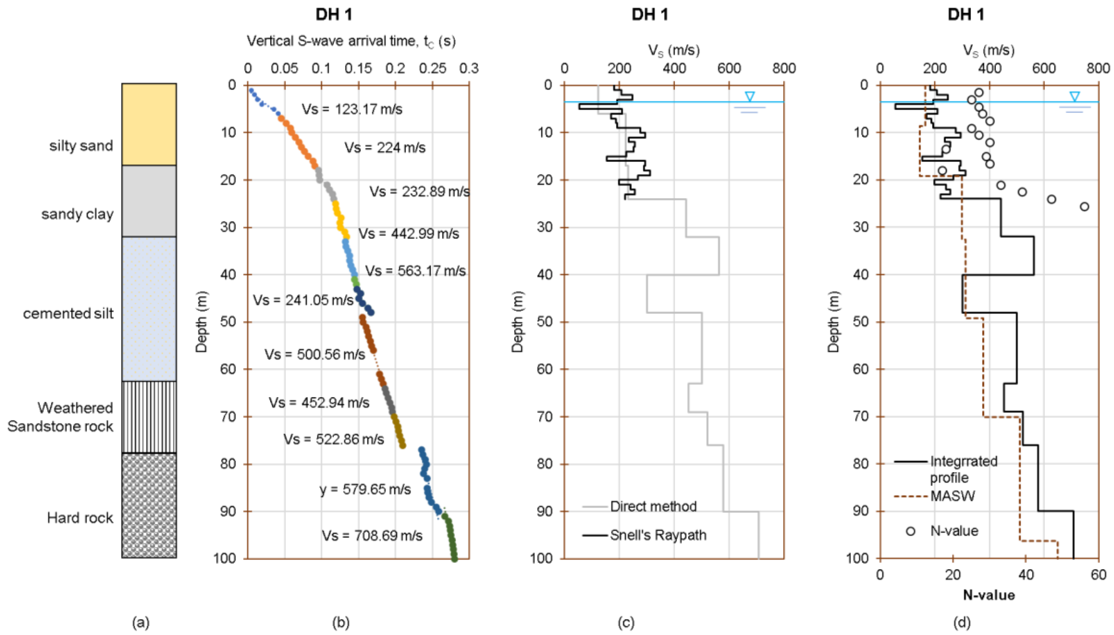

Figure 5. (a) Soil profile from borelog (b) Vertical arrival time for the downhole test at DH 1, (c) V_S from direct method and Snell's Raypath method, (d) V_S from Integrated method and MASW along with SPT N-values

If Snell's Raypath V_S profile is extended to deeper layers, the results can be misinterpreted because of two reasons: (1) there are very low chances for refraction as the wave travel path becomes essentially straight/vertical with an increase in depth (Kim et al., 2004), and (2) The variation in stiffness reduces and layers tend to be more uniform, while Snell's Raypath method can result into highly fluctuating V_S profiles which is not possible in uniform rock/soil layer. Hence, Snell's Raypath method in shallow depth and the Direct method in deeper layers might be a better combination to use for more reliable V_S profiles for deep boreholes.

The depth up to which Snell's Law can be considered useful depends upon the test geometry and soil profile determined from the borelog. V_S profiles from both the methods are shown in Figure 5(c) and Figure 6(c), and combined in Figure 5(d) and Figure 6(d), along with V_S profile from MASW and subsurface profile from borelog (Figure 5(a) and Figure 6(a)). The V_S profile from the MASW test agrees with the downhole results in general, except for a few outlier layers where the difference is high.

N-values obtained from SPT tests at the site are also presented in Figure 5(d) and 6(d). It can be observed that in general, N-values follow the trend similar to the V_S profile, except a few outliers. It is to be noted that hammer energy was not carried out during SPT, which majorly influences the N-values (Anbazhagan et al. 2021). Hence corrected N-values could not be determined. There are a few layers where lower N-values correspond to the higher V_S when compared to subsequent deeper or shallower layers, and vice versa. However, it might not be necessary that an increase in V_S should reflect in N-values as well, especially because of uncertainly in hammer energy, as discussed. Moreover, the fluctuations observed at a few depth, i.e., extreme low values of V_S might not be real, as such soft layer should have been detected in borelog as well.

The layer boundaries are considered at the recording depths which is not often a correct representation of field condition. This assumption may lead to velocity proiles which may have unrealistic fluctuations. Hence, the actual layer boundaries which are derived from borelog need to be considered. However, the borelogs are often made with visual inspection of soil samples obtained from SPT. These may not reflect actual layer boundaries often as these inspections are subjected to human error. Inclusion of soil layer classification based on lab tests can be helpful in such cases. Hence, including actual determined layer boundaries from borelog and lab tests can be considered as a future scope for this study.

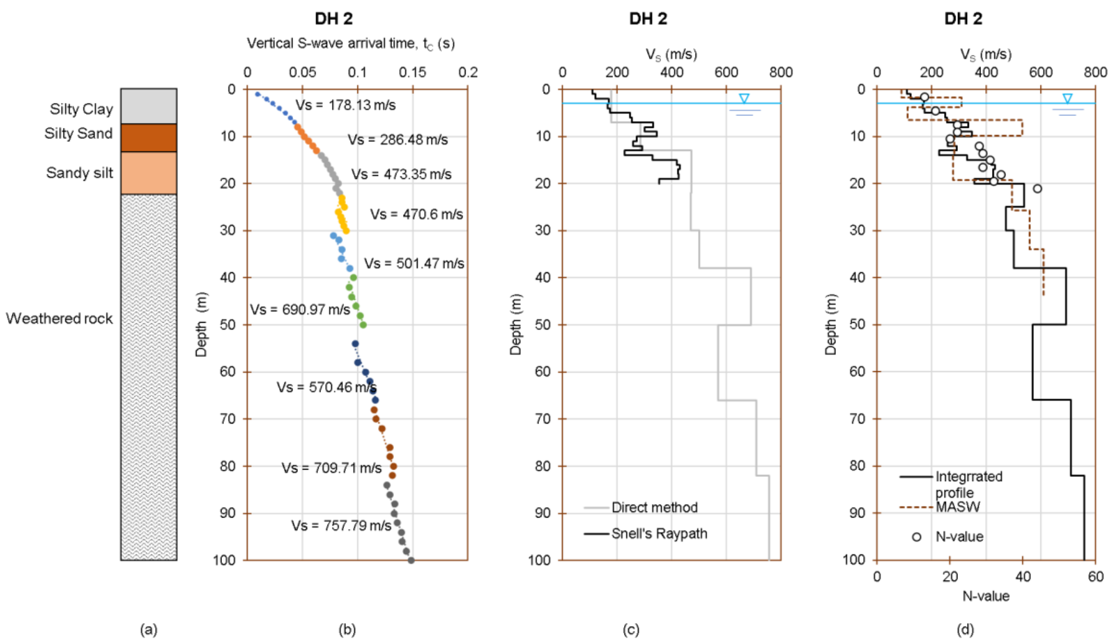

Figure 6. (a) Soil profile from borelog (b) Vertical arrival time for the downhole test at DH 2, (c) V_S from direct method and Snell's Raypath method, (d) V_S from Integrated method and MASW along with SPT N-values

CONCLUSION

Downhole tests were conducted at two locations with silty deposits underlain by sedimentary rocks in East India. The boreholes for the downhole test were prepared based on ASTM 7400 recommendations. Borelog obtained during borehole drilling was utilized in determining the depth of analysis using Snell's Law. V_S profiles for the two locations were generated using an integration of the direct method and Snell's Raypath method. This integrated approach gave a better V_S profile as compared to using a single method alone. However, it still involves the individual generation of two profiles and later integrates them based on shallow and deep soil profiles obtained from the borelog. Moreover, some fluctuations are observed in the profiles obtained from Snell's Raypath method which may not well represent actual field condition because of extreme low or high V_S values. This limitation can be addressed in extended studies where methods can be developed for simultaneously calculating the two profiles and integrating them based on subsurface layer thickness and properties obtained from lab tests.

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REFERENCES

Anbazhagan, P., Kumar, A., Ingle, S. G., Jha, S. K., and Lenin, K. R. (2021). Shear Modulus from SPT N-value with different Energy Values. *Soil Dynamic snad Earthquake Engineering*, 150, 106925.

ASTM International. (2019). *Standard Test Methods for Downhole Seismic Testing*, ASTM D7400-19, Feb. 2019. ASTM, West Conshohocken, Pennsylvania, United States Available: https://www.astm.org/Standards/D7400.htm.

Bang, E. S. (2001). *The Evaluation of Shear Wave Velocity Profiles Using Downhole and Uphole Test*. Masters Thesis, The Department of Civil and Environmental Engineering, KAIST, Daejeon, Korea.

Hwang, S., Menq, F., Stokoe, K. H., Lee, R. C., and Roberts, J. N. (2018). Advanced Data Analysis of downhole seismic records. *Geotechnical Earthquake Engineering and Soil Dynamics V*.

Joh, S. H., and Mok, Y. J. (1998). Development of an Inversion Analysis Technique for Downhole Seismic Testing and Continuous Seismic CPT. *Journal of Korea Geotechnical Society*, Vol. 14, No. 3, pp. 95–108.

Kim, D. S., Bang, E. S., and Kim, W. C. (2004). Evaluation of various downhole data reduction methods for obtaining reliable Vs profiles. *Geotechnical Testing Journal*, vol. 27, no. 6, pp. 585–597.

Mok, Y. J. (1987). *Analytical and experimental studies of borehole seismic methods*. Ph.D. thesis, The Department of Civil Engineering, The University of Texas at Austin, Austin, 1987.

Stokoe, K. H., Hwang, S., Roberts, J. N., Menq, F. M., Keene, A. K., Lee, R. C., and Redpath, B. B. (2017). Deep Downhole Seismic Testing Using a Hydraulically-Operated, Controlled-Waveform Vibroseis. *16th World Conference on Earthquake Engineering, 16WCEE*, Santiago, Chile.