Near Surface Shear Velocity Distribution: Challenges and Solutions

(A case study from Upper Assam Basin, India)

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Abstract

Shear wave is highly sensitive in presence of fluid and fractures in rock matrix. The shallow subsurface typically consists of unconsolidated sediments characterized by very high ratios of compressional (P) to shear (S) wave velocities (Stumpel et al. 1984). One of the challenges associated with imaging of full wave (three component) onshore seismic reflection data (PP, PSh and PSv reflections) lies in the estimation and application of static solutions and assumes critical significance in imaging and generating conformable geological images of the subsurface. Since the shear waves interact in a different manner with the near surface geology, therefore shear statics cannot be approximated by simple scaling of the P-wave statics. One of the most commonly used statics estimation technique employs correlation of an event on a converted wave receiver stack with the same event on the equivalent P-wave stack. However, this approach can be quiet cumbersome in geological regimes that are structurally challenging. Further, large S-wave receiver statics will often degrade the initial velocity estimates that are needed to produce the converted wave stack.

In order to estimate and compute optimum initial velocity for near surface, utilization of direct arrivals in the seismic record is well established practice in the oil & gas Industry. Direct P waves (first arrivals) are used for estimation and computation of near surface P wave velocity distribution in conventional uphole seismic record. Similarly, direct shear waves in full wave uphole seismic records that are farther away from direct P arrivals and nearer to ground rolls (Rayleigh waves; VR = 0.9194 VS, if Poisson's ratio is 0.25) can be used for computation of the near surface shear wave velocity structure. In this methodology, phase identification of direct shear waves in common shot gather domain for full wave uphole seismic data is one of the key initial steps in data processing, analysis and estimation of shear statics. The common receiver gather domain of full wave uphole seismic data have been utilized for extracting a relationship between time versus depth of the direct P-wave and direct S-wave phase in the subsurface (slant ray path converted to vertical ray path). The slope of the time versus depth plots have been employed for estimation of velocities and the intercept time against depth axis have been utilized to compute the thickness of near surface layers. The resultant velocity field derived from this methodology is corroborating well with the near surface investigation carried out in OIL's operational area. It is planned to utilize the proposed methodology to its full potential by designing a full wave uphole grid of 500m x500m in the future multi-component seismic endeavors in OIL's operational areas to estimate the near surface velocity structure and thereby compute and apply the shear wave statics for generating geologically conformable images of the subsurface.

Introduction

Since 21st century, full wave (3C - P, Sv and Sh: three mutually perpendicular directions) seismic data acquisition is being carried out throughout the globe in place of conventional (P wave) seismic data acquisition to get the more sub-surface information for hydrocarbon exploration. Full wave seismic data acquisition is based on principle of "energy partitioning and wave conversion (P↔S) at the rock boundaries or reflectors".

In an isotropic and homogeneous medium the velocity of primary waves (V_P) is given by

$$V_P = [(\lambda + 2\mu)/\rho]^{1/2} = \left[\frac{E(1-\sigma)}{\rho(1-2\sigma)(1+\sigma)}\right]^{1/2}$$

where λ and μ are Lame´'s constants, E is Young's modulus, and σ is Poisson's ratio. (Sheriff and Geldart 1995, 44-45).

Moreover, **Shear body wave** in which the particle motion is perpendicular to the direction of wave propagation, are generated by the incidence of P-waves on interfaces at other than normal incidence, whereupon they are called **converted waves,** SV-waves.

In an isotropic and homogeneous medium the velocity of shear waves (*Vs)* is given by

$$V_s = (\mu/\rho)^{1/2} = \{E/[2\rho(1+\sigma)]\}^{1/2},$$

where μ is the shear modulus, ρ is the density, E is Young's modulus, and σ is Poisson's ratio.

S-waves have two degrees of freedom (horizantal shear, Sh and vertical shear, Sv) and can be polarized in various ways.. This paper describes the challenges and assumptions for near surface scenario and subsequent phase observations of both direct P wave and shear wave in original full wave uphole seismic data that helps to compute near surface velocity distribution & static solutions. These statics can be utilized in full wave onshore seismic reflection data to improve the image resolution. Schematic ray path of full wave onshore seismic reflection data where explosive used as a seismic energy source is showed in the Fig. 1.

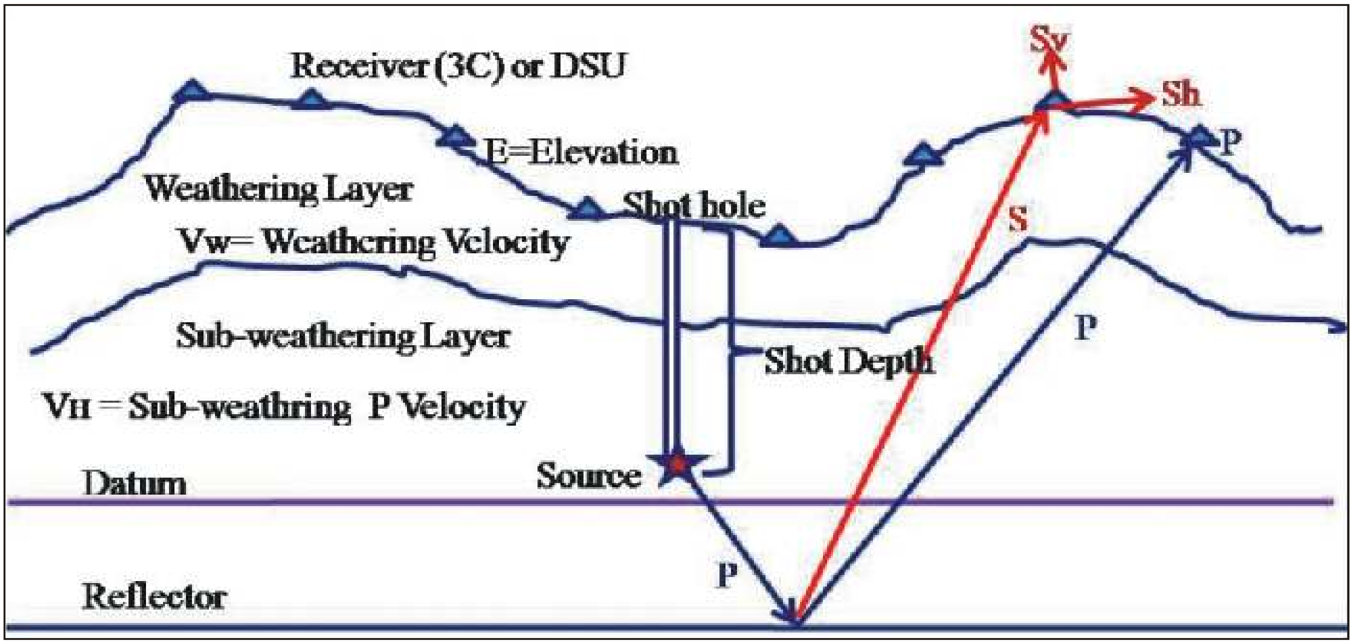


Fig. 1: Schematic ray path of full wave onshore seismic reflection data. Three component (3C) receivers are laid out on surface at varied elevated topography. P energy is splited as P and S & conversion of wave (P↔S) takes place at the reflecting point on the reflector.

Challenges and assumptions for near surface : Underlying the concept of conventional static corrections is the assumption that a simple time shift of an entire seismic trace will yield the seismic record that would have been observed (1) if the geophones had been displaced vertically downward (or upward) to the reference datum, an assumption not strictly true, especially if the surface-to-datum distance is large, and (2) that the sub-datum velocity does not change horizontally.

Conventional static correction methods are most apt to fail where there are (1) large rapid changes in the topography or base of weathering, (2) horizontal velocity changes below the weathering, thus violating the assumption that the sub-datum velocity does not vary significantly, (3) large elevation differences between the datum and the base of the weathering, or (4) inadequate controls on long-wavelength statics. Large seafloor relief is apt to be associated with horizontal velocity changes that cannot be compensated with static corrections.

Statics and solutions: Corrections applied to seismic data to compensate for the effects of variations in elevation, near-surface low-velocity layer(weathering) thickness, weathering velocity, and/or reference to a datum. The objective is to determine the reflection arrival times which would have been observed if all measurements had been made on a (usually) flat plane with no weathering or low-velocity material present. These corrections are based on uphole data, refraction first-breaks event smoothing, and sometimes other geophysical methods. The most common convention is that a negative static correction reduces the reflection time.

a) **Uphole-based statics** involve the direct measurement of vertical traveltimes from a buried source. *This is usually the best static-correction method where feasible.*

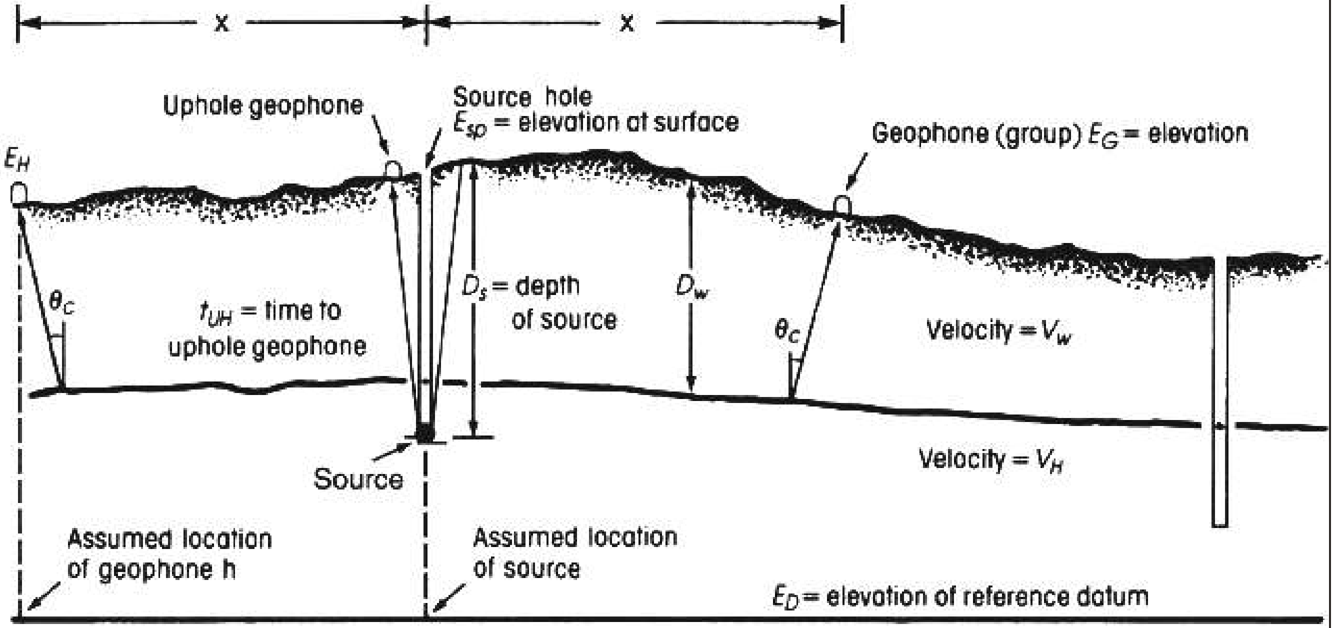
b) **First-break statics** are the most common method of making field (or first-estimate) static corrections, especially when using surface sources.

c) **Data-smoothing statics methods** assume that patterns of irregularity which events have in common result from near-surface variations and hence static-correction trace shifts should minimize such irregularities. Most automatic statics-determination programs employ statistical methods to achieve the minimization. Data-smoothing methods are generally applied to remove small residual errors after first applying methods a) or b). Second-order statics corrections are often called **trim statics** (Sheriff and Geldart,1995, 261–268, 303–307, 474, and Cox ,1999).

Static correction equations based on first-break intercept time and its tentative pictorial representation for conventional onshore seismic reflection data is shown in the following Fig. 2.

<u>**Near surface shear wave challenges and solutions:**</u> Shear waves statics are often appreciably different and much larger than P-wave statics. Shear wave is highly sensitive in presence fluid in rock matrix. The shallow subsurface typically consists of unconsolidated sediments characterized by very high ratios of compressional (P) to shear (S) wave velocities (Stumpel et al. 1984) where λ (Lame´'s constant-fluid incompressiability) plays a key role.

Estimation of near surface shear velocity structure is one of the challenges to compute optimum shear statics (receiver statics) in full wave onshore reflection seismic data. Direct P wave arrivals are utilized in conventional uphole seismic data for estimation & calculation of near surface P wave velocity distribution. Similarly *utilization of direct shear wave information is possible in full wave (Three components)*



Excess time = t_{xs} = vertical time through weathering − time at subweathering velocity

$$t_{xs} = D_W(1/V_W - 1/V_H) = t_i\sqrt{\frac{V_H - V_W}{V_H + V_W}} = t_iK, \text{ where}$$

t_i = intercept time for refraction first breaks, and

$K = [(V_H - V_W)/(V_H + V_W)]^{1/2}$.

For source below the datum

$$D_W = (t_{UH} - D_S/V_H)/(1/V_W - 1/V_H)$$
$$= V_W(t_{UH}V_H - D_S)(V_H - V_W)$$
$$= t_iV_W/\cos\theta_c, \text{ where}$$

θ_c = critical angle = $\sin^{-1}(V_W/V_H)$.

Correction to effectively place source and geophone on datum = t_c:

$$t_c = (E_{SP} - D_S - E_D)V_H + (E_G - E_D)/V_H - t_{xs}.$$

For source in the weathering (or at the surface where $t_{UH} = 0$),

$$D_W = \tfrac{1}{2}V_W(t_i/\cos\theta_c + t_{UH}).$$

Differential weathering correction = difference between corrections for geophones at G and H:

$$t_{DWC} = (t_H - t_G)(1 - V_W/V_H) + (E_H - E_G)/V_W.$$

Fig. 2: Static correction equations based on first-break intercept time.

uphole seismic data for estimation and calculation of the near surface shear velocity distribution. In this paper phase observations of direct P waves and direct shear waves in common shot gather domain has been made on full wave uphole seismic data in one of the OIL's operational areas of Upper Assam in India. These phases are apparently similar in shape and observed as *arch shaped events* but not same which depends on near surface average velocity distribution of both P and Shear waves. Common receiver gathers of vertical sensor's uphole seismic data and North-South sensor's uphole data have been analysed in terms of time – depth relationship. The near surface information in terms of layer thickness and velocities for both the P-wave and shear wave has been derived on the basis of these relationships.

Full wave uphole seismic survey:

Geometry of the survey: A total of 12 nos. of digital three component sensors (DSUs) are laid out on either side of drilled hole. The sensors are placed on the surface at an interval one meter. The 12th and 13th DSUs are planted one meter away from the drilled hole. Detonator is used as a seismic energy source in drilled hole at the following depth series for shot gathers from bottom to top.

Depth series: 100, 90, 80, 70, 60, 55, 50, 45, 40, 35, 30, 25, 22, 19, 16, 13, 10, 7, 5, 3, 1 in feet.

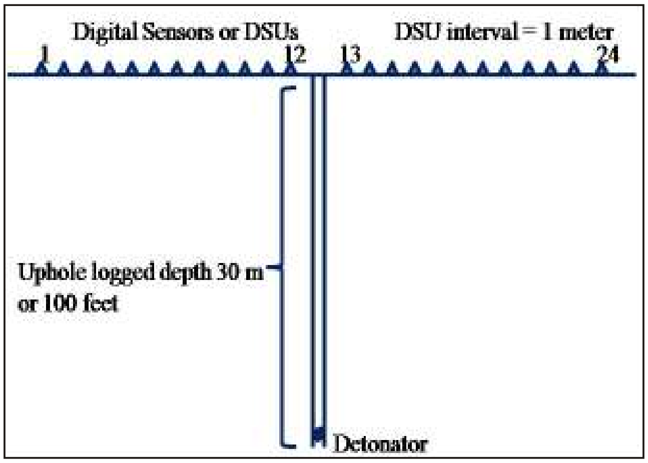


Fig. 3: Schematic geometry of full wave uphole seismic survey. Receivers or sensors or DSUs(24 Nos) are laid out at about 1m apart on both the sides of drilled hole of drilled depth 30 m. Detonator is used as energy source.

Direct ray path of shot receiver gather: It associates with arch shaped event, useful to identify the phase of direct arrivals in the seismic record. Energy from blasted seismic source spherically spreads out in all directions in the subsurface. Arch shaped events for direct arrivals are expected in seismic record as digital sensors are planted at equi-spaced about one meter apart on the surface on either side of drilled hole.

Direct ray path of common receiver shot gather: It associates with Time-Depth relationship. In uphole seismic survey, seismic source is blasted from bottom to top of the drilled hole. Hence seismic records in shot gather domain are associated with different depths in the drilled hole. Fundamentally, near offset first arrivals are direct P waves in the seismic record. It is good to make near offset receiver gather from all shot gather records. After applying the time correction (slant ray path converted to vertical ray path), time-depth plots can be prepared.

Full wave uphole Raw seismic data: Uphole data has been acquired with 0.25 ms sample interval of 2 sec record length.

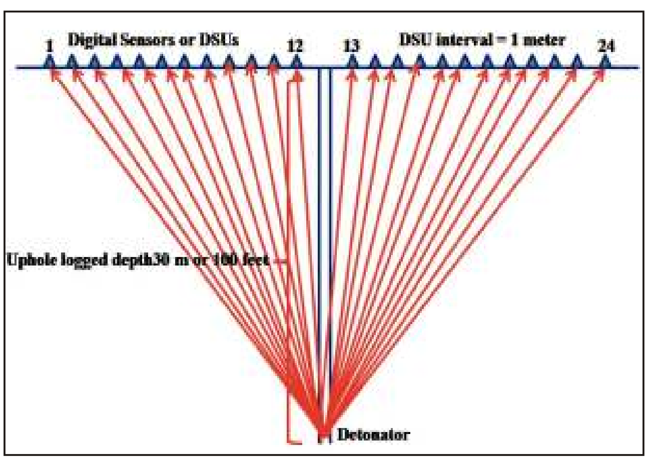


Fig. 4: Schematic direct ray path of common shot gather in full wave uphole seismic survey for homogeneous isotropic media.

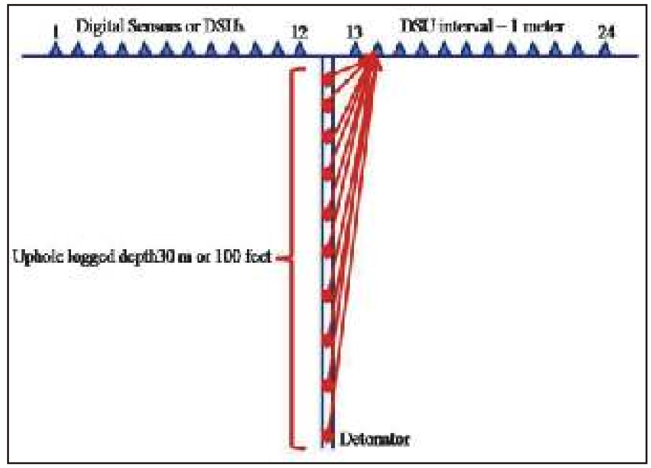


Fig. 5: Schematic direct ray path for common receiver-shot gather in full wave uphole seismic survey for homogeneous isotropic media.

Since total of 24 DSUs are planted on the surface, raw shot gather contains 72 traces in which 24 traces belongs to Vertical sensor gather, 24 traces belongs to East-west sensor gather and rest 24 traces belongs to North-South sensors gather. One of such representative shot gather is showed in Fig. 6.

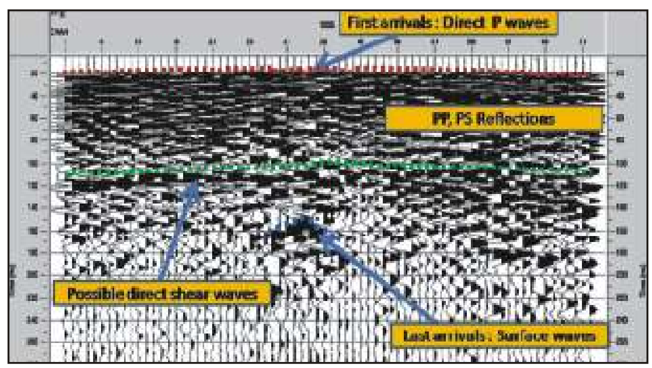


Fig. 6: Raw shot gather for source depth at 70 feet of full wave uphole seismic data. Note Direct P (Red colour dotted curve), PP reflections, PS reflections, Shear energy (possible direct Shear, green colour dotted curve) followed by surface waves (ground roll, blue colour dotted curve).

A few of such uphole shot gather data comprises 72 traces at 55 feet, 35 feet, 16 feet of source depths, can be segregated as Vertical , North-South and East-West sensors data and they are showed in Fig. 7.

Direct shear waves are clearly noticed in shot gathers of North-South sensors data for all shot depths compared to that of East-west sensors data. Therefore, phase analysis has been made on North-South sensors data for direct shear waves.

Phase of direct wave arrivals in full wave uphole raw shot gathers: Fundamentally seismic energy spreads spherically in all directions from the blasted seismic source, the direct P or S-waves can be appeared as arch shaped

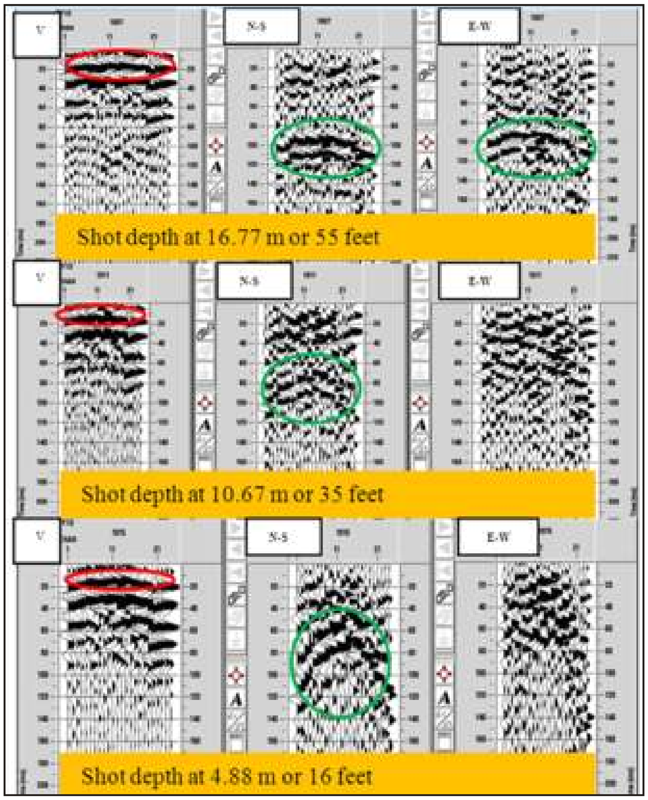


Fig. 7: Band pass (6-12-60-70) applied full wave uphole shot gathers of Vertical (V), East-west (E-W) and North-south (N-S) sensors (Left to Right). Note arch shaped events with high energy indicate the direct waves. Possible phase of direct P waves are highlighted in red colour and for direct shear waves, it is highlighted in green colour.

events or hyperbolic events in an uphole shot gathers. Therefore, phase of direct wave arrivals of both P and shear waves in uphole shot gathers could be similar but not same which depends on velocity distribution and appears as arch shaped events is shown in Fig. 8. Basically, recorded waves at DSUs were passing through all possible layers in the near surface from seismic source. Therefore, the arrival times of direct waves which are in arch shaped events in shot gathers could be due to average velocity of all possible layers. *At constant source depth, direct P-waves show the broader arch shaped event compared to that of direct shear waves in the uphole seismic data. Deeper the shot depth, broader the arch shaped event of direct waves, as the average velocity of direct waves are normally more at deeper shot depth than that of at shallow shot depth*. Common receiver-shot gathers can be generated from all shot gathers. Since near offset first arrivals are direct waves, direct wave analysis can be easily done on near offset receiver-shot gathers to give the direct relation between depth and arrival times for near surface information in terms of velocity and thicknesses of the layers

Common receiver gathers of both vertical sensor data and North-South sensor data which is 14th DSU data is shown in Fig. 9 & 10.

Based on the time information of phase of direct shear arrivals in shot gathers and respective time information in common receiver gather are collectively guide the time breaks of direct shear arrivals. These times are in general, wave slant path times that have been corrected as vertical path times.

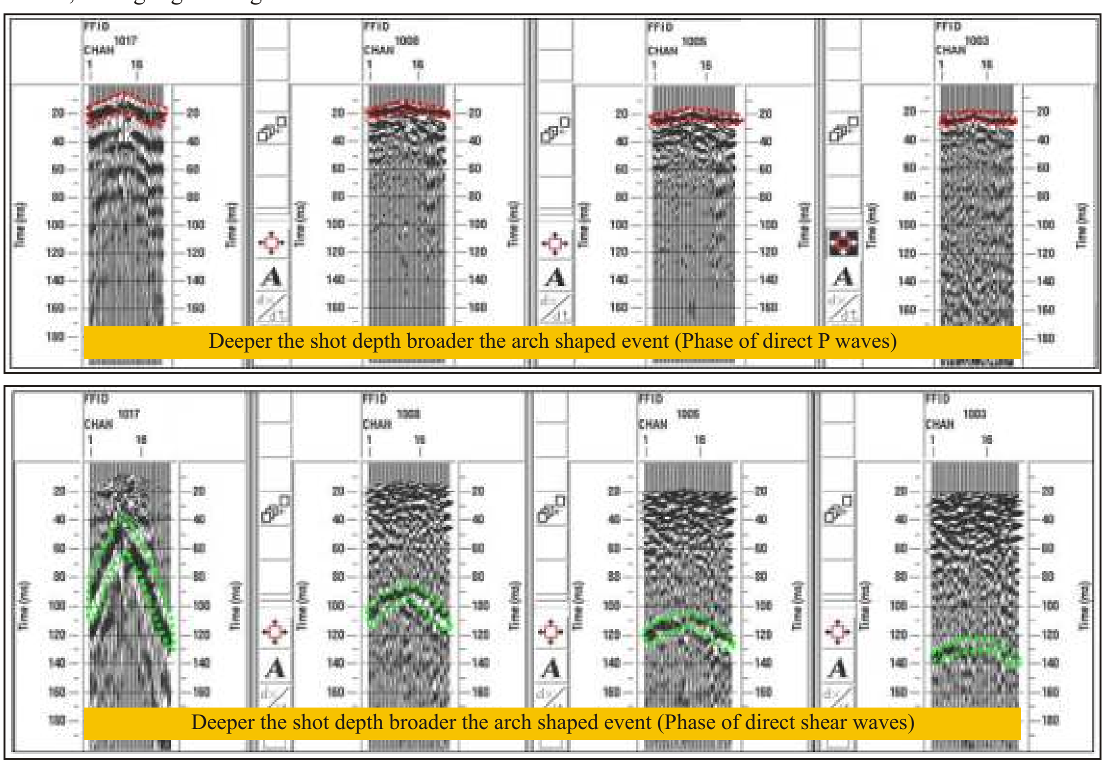


Fig. 8: Uphole shot gathers of Vertical sensor's (top) & North-south sensor's (bottom) data for shot depths 10 feet, 50 feet, 70 feet & 90 feet(Left to Right). Note arch shaped events with high energy indicate the direct P waves(highlighted in red colour). & direct Shear waves (highlighted in green colour).

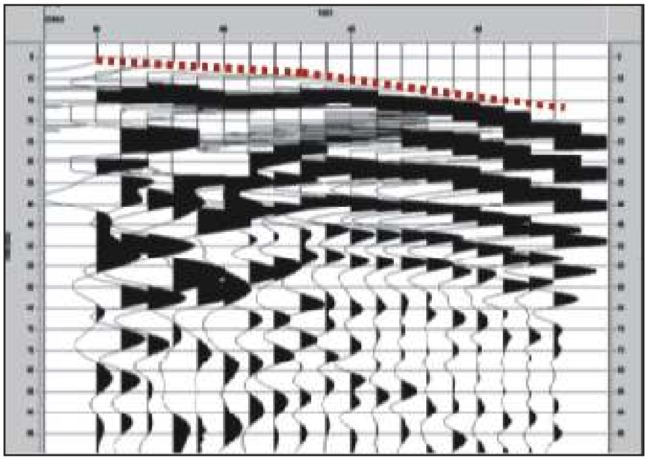


Fig. 9: Near offset common receiver gather of vertical sensor. Note direct P-wave time breaks are highlighted in red colour dotted line.

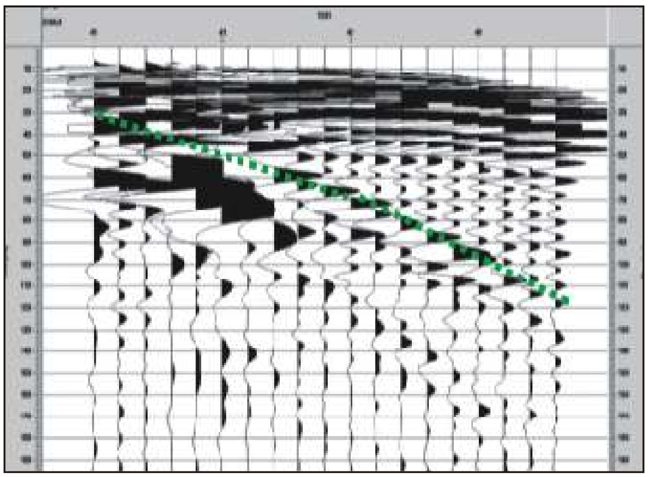


Fig. 10: Near offset common receiver shot gather of North-South sensor. Note direct shear-wave time breaks are highlighted in green colour dotted line

<u>Time-Depth Plots for direct P and shear waves:</u> Time breaks of direct P-waves, direct shear waves and depths information helps to compute near surface information in terms of layer velocities and thicknesses are shown in Fig. 11 & 12.

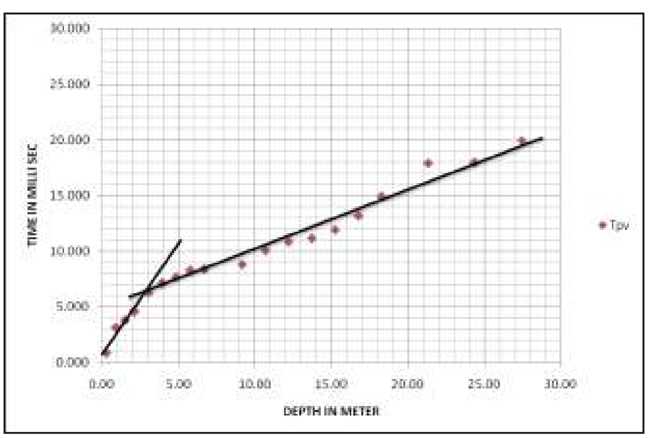


Fig. 11: Time-depth plot for direct P-wave information shows two velocities for possible two layer case

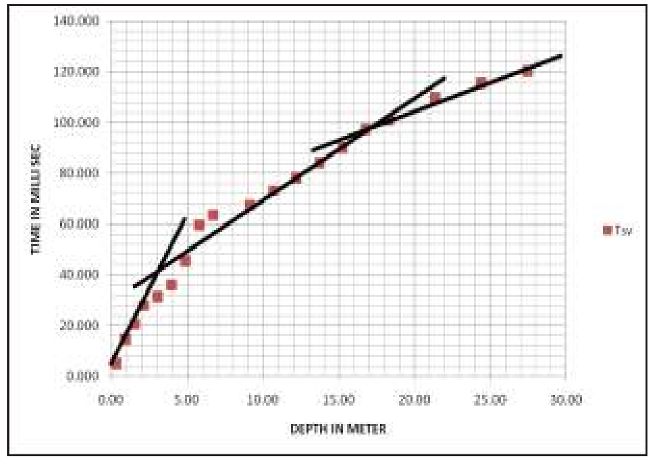


Fig. 12: Time-depth plot for direct S-waves shows three velocities, may be due to presence of fluid in second layer.

<u>Interpretation for direct P waves</u>: Direct P wave information suggests two layer case where first layer (weathering layer) velocity is 500 m/s and its thickness is 3 m and below weathering layer, velocity is 1820 m/s

<u>Interpretation for direct shear waves:</u> Direct shear wave information suggets three velocities within two layer case as 100 m/s, 208 m/s and 460 m/s as shear is sensitive in presence of fluid in rock matrix. Pictorial representation of interpretation of full wave near surface velocity distribution with respect to depth is shown in Fig. 13.

<u>Full wave uphole - based statics - Multi-componenet onshore seismic data:</u> There are basically three shotgathers i.e., vertical sensor gather, east-west sensor gather and north-south sensor gather in multi-component seismic data. Vertical sensor gather is fully associated with P wave where as rest of

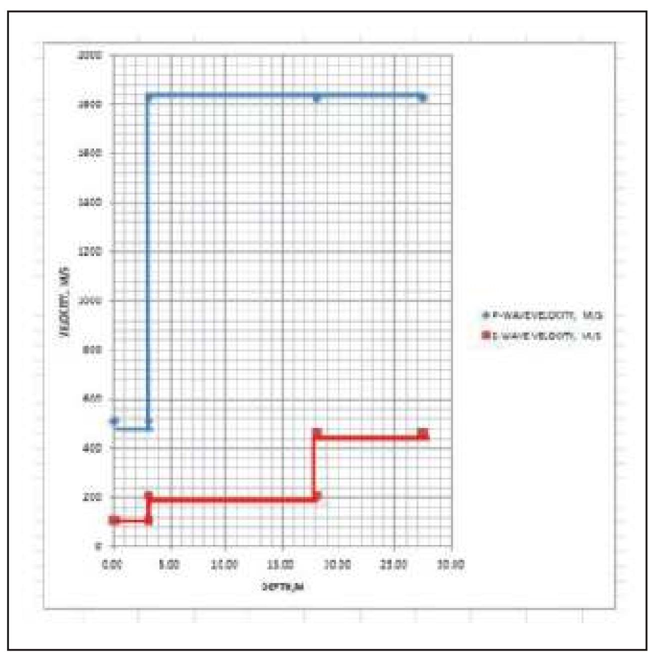


Fig. 13: Pictorial representation of interpretation of full wave near surface velocity distribution with respect to depth.

the gathers are associated with P wave on source side and shear wave on sensor side.

Full wave Uphole-based statics involve the direct measurement of vertical traveltimes from a buried source and hence is usually the best static-correction method where feasible. Full wave Uphole grid of 500m x 500m in any study area, if feasible could be able to compute and generate near surface velocity & thickness models, elevation models and V_P/V_S models. All these models helps to compute statics to all source and receiver points for both P wave and shear wave in Multi-component onshore seismic data. Statics are in Multi-component data as follows

- Statics computations for vertical sensordata as similar as in conventional seismic data
- There are three nos of equal P - wave source statics for all three shot gathers (Vertical, east-west and north-south sensors data)
- One no. of P- wave receiver statics for vertical sensor data.
- Two nos of shear wave receiver statics for east-west and north-south sensor data. Near surface V_P/V_S ratio model plays a significant role to compute optimum shear wave receiver statics from the following formula.

Shear wave receiver statics = (V_P/V_S) * P wave receiver statics

Recommendations

- In place of conventional uphole seismic surveys, full wave uphole seismic surveys will be recommended for the full wave onshore seismic reflection data
- Since shear wave is polarized wave, it is recommended to acquire full wave uphole seismic data in two mutually perpendicular seismic profiles which are crossing at drilled hole to get the much more information of direct shear energy to enhance the confidence of phase identification of direct shear energy.

Conclusion

Phase identification of direct arrivals of both P and shear wave is possible in full wave uphole seismic data. The time breaks of both direct P-wave and direct shear wave in the full wave uphole seismic data helps to know the near surface P and shear wave velocity distribution.

Acknowledgement

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