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SHALLOW SUBSURFACE CHARACTERIZATION USING MULTI-CHANNEL ANALYSIS OF SURFACE WAVES IN THE NIGER DELTA

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Abstract: Surface waves are considered one of the most challenging forms of noise found on body wave records and lots of efforts have been made at their attenuation. However, their dispersive properties have been found to be usable for inferring near-surface elastic properties. In a reflection data acquisition programme in SPDC's 'X' prospect in the Niger delta, a suite of low frequency and high amplitude waves was recorded in addition to the normal reflection/refraction and direct waves present. Their low group velocity and high amplitude character identify them as surface waves. Using the Multichannel Analysis of Surface Waves (MASW) technique these waves were analyzed to produce shallow subsurface shear wave velocity profiles in the field, based on which a map of the distribution of optimum shot burial depths, that would be necessary for effective ground roll attenuation and for deep penetration of substantial seismic energy in this field was generated. The results obtained here are also applicable for static correction, accurate velocity model building and for other environmental and geotechnical studies.

Key words: Dispersive, Multichannel analysis, Attenuation, Shot burial depths, Seismic energy

INTRODUCTION

In seismic reflection imaging the distortive effects of the shallow subsurface, caused by its variable thickness and low velocity abnormalities as well as the issues of seismic energy entrapment in the shallow low velocity layer have been a source of concern in deep structure imaging. Although there are effective ways of seismic noise attenuation in seismic data processing, especially the suppression of ground rolls, the deficiency in low frequency energy for deep penetration have been a long standing concern of seismic exploration teams. These challenges however, can be better handled if the shallow subsurface is adequately characterized. With the fast depletion of relatively shallow hydrocarbon reserves necessitating the probing of deeper reservoirs, it becomes very imperative for the shallow subsurface to be adequately characterized, as effective imaging of deeper structures will depend largely on how well the near surface layers are known.

In this study, the Multi-channel Analysis of Surface Waves technique was applied for the characterization of the shallow subsurface in an SPDC X field, within the Niger Delta region. In general, surface waves are considered to be noise on body-wave records. However, the dispersive properties of surface waves can be exploited to infer near-surface elastic properties (Park et.al, 1998, Xia et.al, 2000). Thus, here an attempt is made to use this noise to enhance our capabilities and facilitate our ability to solve some more problems facing the seismic explorationist in the field.

The estimation of subsurface mechanical properties by using surface waves was proposed by seismologists for the investigation of the earth's crust and upper mantle (Dorman et al, 1960). Later, Ebeniro, et al., (1983), made use of surface waves recorded during a refraction survey in Refugio County, Texas to obtain continuously varying compressional and shear wave velocity profiles of the shallow subsurface in the area. This study was one of the earliest applications of surface waves for the determination of near surface characteristics needed for exploration. Also in the 1980s, Spectral Analysis of Surface Waves (SASW) was introduced to generate near-surface Vs profiles (Nazarian et.al, 1983). This method uses the spectral analysis of ground roll generated by an impulsive source and recorded by a pair of receivers. However, due to the uniqueness of each site, inherent difficulties are encountered when analyzing and distinguishing signal from noise besides being expensive. A relatively refined and recent replacement for Spectral Analysis of Surface Waves is the Multichannel Analysis of Surface Waves, which produces more accurate results and allows for an effective coverage of large areas in continuous mode.

LOCATION

The field of study is SPDC's 'X' field, located in the Niger delta, about 44 kilometres northeast of Port Harcourt. The Niger delta basin is situated on the continental margin of the Gulf of Guinea, in equatorial West Africa, at the southern end of Nigeria bordering the Atlantic ocean between latitudes 3º and 6º, and longitudes 5º and 8º. The delta is underlain by three stratigraphic units, the deepest Akata Formation, the middle Agbada Formation and the top Benin Formation. The Benin Formation is mainly made up of continental sand deposits with intercalation of shale and is covered with the topmost low velocity layer which, in most cases is weathered. Immediately below the Benin Formation is the reservoir sand of the Agbada Formation which is believed to house the oil and gas resource of the Niger Delta. The Akata Formation is also believed to be the source rock for the petroleum resource. To gain a better understanding of the deeper structures will require very good knowledge of the shallowest Benin Formation and its low velocity cover. It is within this low velocity layer that low frequency surface waves are normally generated; especially when the field acquisition parameters are not chosen to reduce their excitation.

METHODOLOGY

The methodology of MASW involves three main stages; data acquisition, dispersion curve generation and shear wave velocity inversion. The data used for this analysis is a 3-D land seismic data, acquired using the conventional CMP configuration utilized for seismic reflection surveys. Twenty seven (27) shots were analyzed; for each shot, an average of about 900 geophones at approximately 50m spacing, arranged into a varying number of receiver groups recorded seismic events. Since the MASW method requires 2-D lines as input, parallel lines of receiver records were first extracted from the 3-D data. The data was thus segmented into seven receiver lines that stretch from north to south in the field of study (Figure 1)

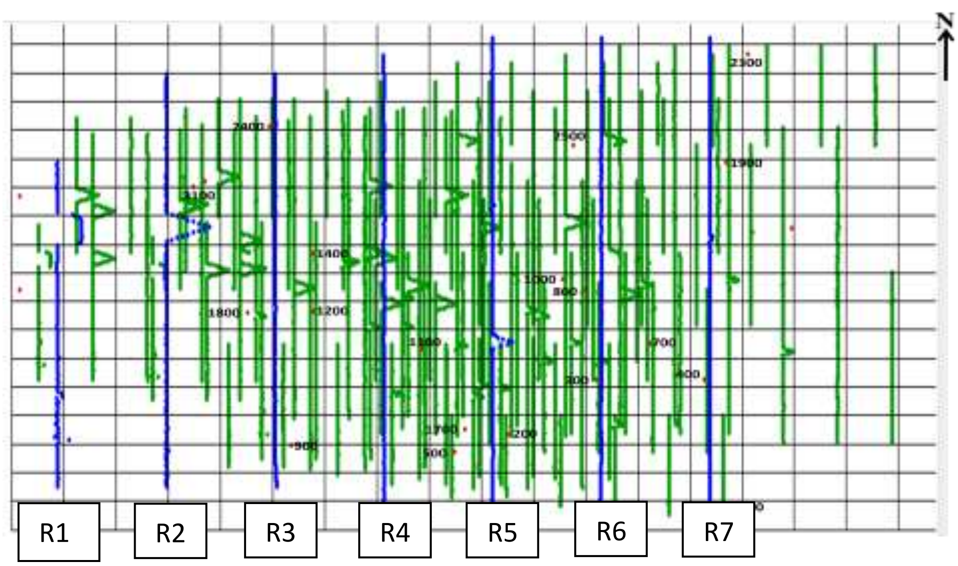

Figure 1: Sketch of the Base map showing seismic shot positions (red dots with shot numbers), receiver lines (blue lines) and the CMP lines (green lines).

The data was then filtered to attenuate noise; since the data was acquired as a conventional reflection data, it was necessary to filter off all other wave forms including primary reflection signals as they constitute noise in this analysis. The filtering was carried out in the F-K domain. It is important to note that one of the advantages of this methodology is the fact that noise inclusion, affects the accuracy of the output minimally, owing to the usual very large amplitudes of Rayleigh waves compared to other signals, thus simple filtering is adequate for the process.

The dispersion panels were extracted using the modified wave-field transform (Park et al., 1998). When a Fourier transform is applied to raw surface wave data plotted on the x-t domain, where u(x,t) represents an entire shot gather, the Fourier transformation results in U(x,ω).

$$U(x,\omega) = \int u(x,t)e^{-i\omega t}\,dt$$

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U(x,ω) is then deconvolved and can be expressed in terms of phase and amplitude.

$$U(x,\omega) = P(x,\omega)A(x,\omega)$$

……………………… 2

where P(x,ω) is the phase portion of the equation that holds information containing the waves' dispersion properties, including arrival time information and A(x,ω) is the amplitude portion that contains data pertaining to the attenuation and spherical divergence properties of the wave. Since P(x,ω) contains the dispersion property information, the equation can be written in the form

$$U(x,\omega) = e^{-i\Phi x}A(x,\omega)$$

……………………… 3

where $\Phi=\omega/c_\omega$, ω is the frequency in radians, and c_ω is the phase velocity for frequency ω. This data can then be transformed to give velocity as a function of frequency:

$$V(\omega,\Phi) = \int e^{i\Phi x}\frac{U(x,\omega)}{|U(x,\omega)|}\,dx$$

………………………… 4

This will yield a dispersion image showing a variation of phase velocities with frequency. Figure 2 shows a set of typical dispersion images obtained from two shots, from which the frequency and phase velocity bands of the data set can be observed. The images show that the data is dominated by fundamental mode Rayleigh waves.

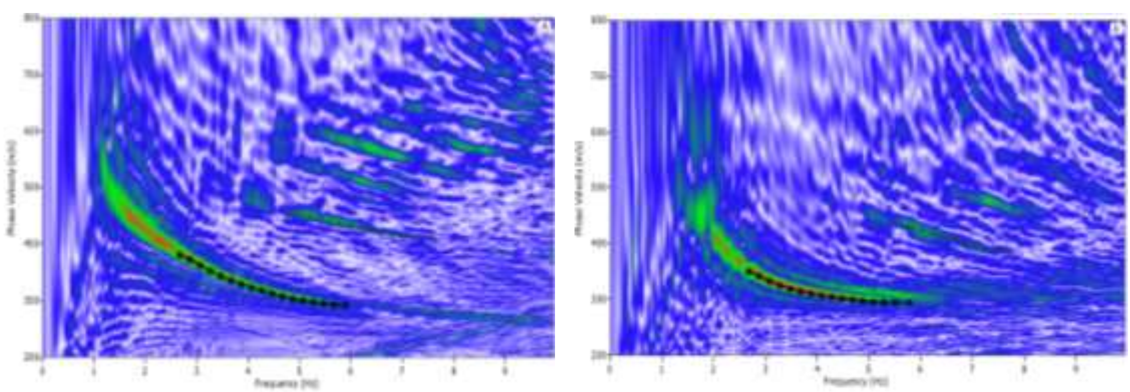

Figure 2: Typical dispersion images showing picked dispersion curves

The least squares curve fitting method was employed for the inversion. The curve fitting technique requires initial model parameters to be supplied and then the algorithm, through an iterative process fits theoretical curves generated based on the initial model parameters with the experimental data to obtain the best fit, while modifying the parameters of the model. In order to supply parameters for the initial model of each of the data sets, the dispersion curves are examined to determine the maximum recorded wavelength, and based on its value, the maximum depth (depth to half space) of the initial model is determined. For our inversion, the depth to half-space was set at a maximum value of 100m. This depth was determined using the observation from the dispersion panel where the fundamental mode has a phase velocity of about 400 ms^{-1} at a frequency of 2 Hz. An initial density value of about 2110kgm^{-3} was assumed. This is the density of poorly consolidated sandstone reported by Mavko et al., (1999). The Poisson's ratio is calculated to be 0.34. The total number of layers was set to be 10 for convenience. These initial parameters were supplied in all cases for the inversion. The inversion process produces 1-D Vs models, for the midpoints of receiver spreads for a particular shot. Figure 3 shows typical 1-D Vs profiles obtained for one of the receiver lines. However, by the arrangement of several shots on a receiver line, a 2-D profile of shear wave velocities is obtained.

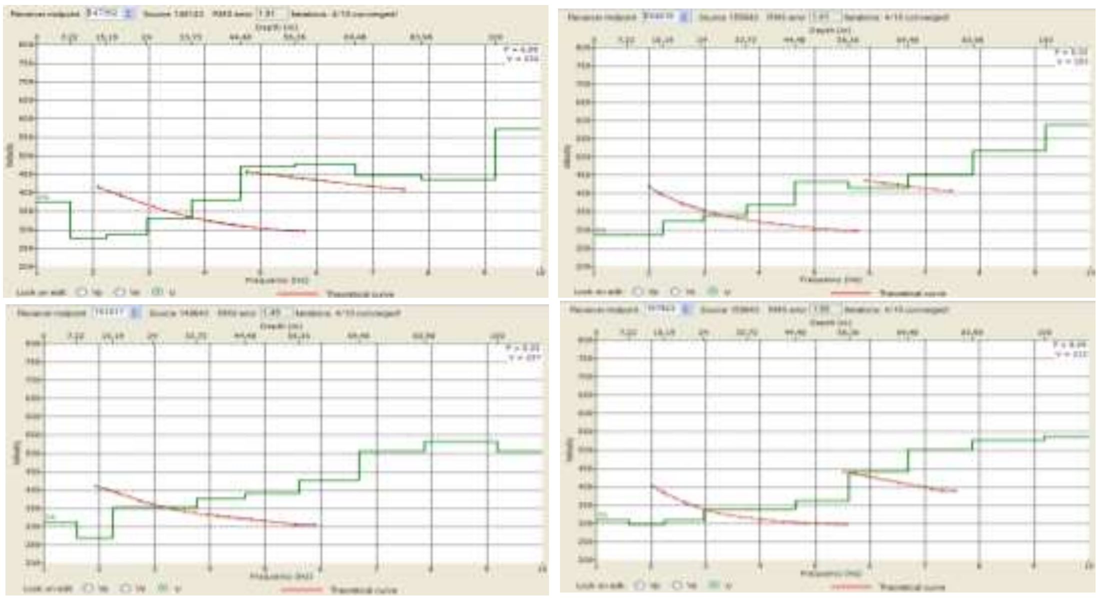

Figure 3: Typical 1-D Vs models obtained for one of the receiver lines

RESULTS

The 2-D shear wave velocity (Vs) profiles generated in this analysis are shown in figure 4. They are obtained by sequentially arranging and interpolating between 1-D Vs models obtained for mid points of receiver spreads for each shot on the receiver lines. The Vs profile for receiver line 1 (Fig. 4a), shows a top layer having Vs of between 300ms^{-1}- 330ms^{-1}. This layer which would have been a thick and fairly uniform layer spanning the entire profile, is seen to be thinnest on the southern flank, being underlain by a lower velocity (200-250ms^{-1}) layer. This lower Vs second layer observed has a maximum thickness of about 10m on the south and thins out towards the northern flank, truncating just before the 151750 location of the profile. Below about 15m depth, the profile shows that layer velocities increase smoothly down to about 97m, where another low Vs (400-450ms^{-1}) layer, underlies an upward dipping north-south extension of a localized, high Vs feature observed on the northern edge. Figure 4b shows Vs values that increase steadily with depth only for the southern flank of receiver line 2 Vs profile. Beyond the 149000 receiver point from the south, velocity reversals are observed at several depths. The northern flank of the profile shows a localized high velocity layer at the surface, underlain by a lower velocity layer, which seems like a continuation of the low velocity top layer extending from the south. The profile also shows a high velocity layer extending from the southern flank of the profile towards the north, between 68-100m depth. This layer which is sandwiched between two lower Vs layers for parts of its length is found to extend, occupying down to the half space, beyond the 152000 point of the profile. The velocity of this feature is observed to be higher in the south than in the thicker portions of it, lying from the central to northern flank of the profile.

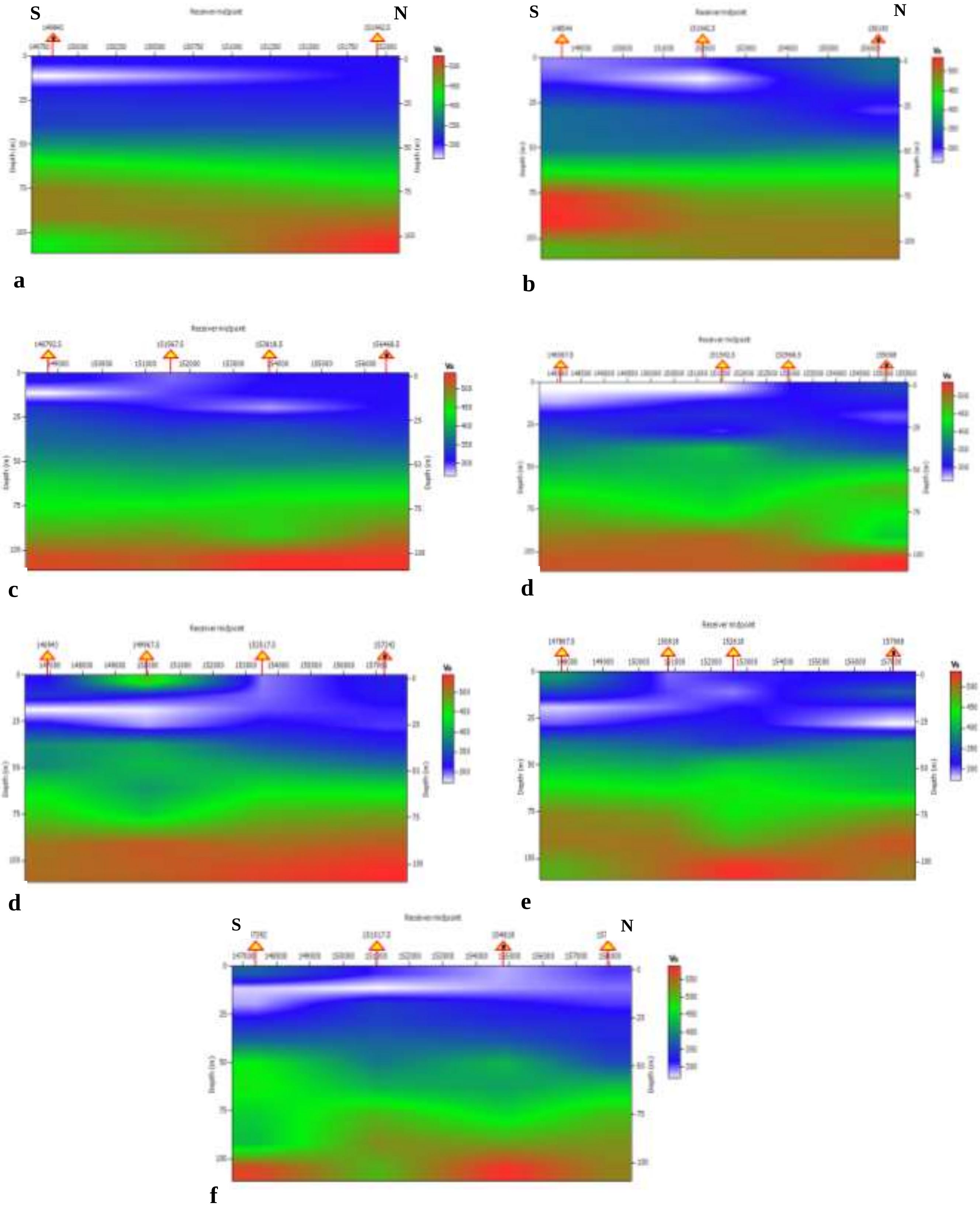

Figure 4: 2-D Vs profiles for (a) receiver line 1 (b) receiver line 2 (c) receiver line 3 (d) receiver line 4 (e) receiver line 5 (f) receiver line 6 (g) receiver line 7.

The Vs profile obtained for receiver line 3 (Fig. 4c), shows a top layer having Vs of about $340ms^{-1}$, to be underlain by a second layer of Vs $250ms^{-1}$. The top layer which is thinnest at the southern flank of the profile spans almost the entire profile except for the localized region between 151000-153000 receiver points where the lower Vs layer outcrops at the surface. The extreme north of the profile shows Vs increasing steadily from the surface to the half space. In general, the profile exhibits only slight lateral variation in the thicknesses of formations based on the observed velocity distribution. The receiver line 4 profile (Fig. 4d), shows a low Vs ($220ms^{-1}$) top layer of varying thickness extending from the southern flank of the profile towards the north, where it is truncated by a higher Vs feature that stretches from the 152500 receiver point to the northern edge of the profile. From the south up to about 149500 receiver point, the velocities of layers are observed to increase continuously with depth, while for the edge of the northern flank, velocity reversals are observed at between 20-25m, 55-60m and 85-90m respectively. Also around the 151542.5 receiver midpoint location a localized region with slight Vs reversals at several depths is observed.

The top layer of profile line 5 (Fig. 4e), exhibits a laterally varying Vs of about $350ms^{-1}$- $470ms^{-1}$. This layer stretches from the southern flank of the profile to the point 153517.5 along the profile, where a thick low velocity zone ($250ms^{-1}$) truncates it. Beyond this low velocity zone, the edge of the northern flank has velocity values of about $320ms^{-1}$. Beneath the top layer at the southern flank, Vs drops to less than $250ms^{-1}$, forming an extensive low velocity layer within the depth range of 16-27m, which spans the entire profile. Below this low Vs layer, velocity increased steadily with depth down to the half space on the north, while from the south to about the centre, velocity reversals are observed within the depth range of 30-70m. For receiver line 6 (Fig. 4f), the profile shows that the Vs of the top layer varies laterally, having values of about $380ms^{-1}$ on the southern flank and less than $280ms^{-1}$ from the 150000 to 154000 receiver points, where the velocities begin to increase northwards. The second layer, which is a low Vs ($250ms^{-1}$) layer, extends from the thick low velocity zone that appears at the surface around the central region, to underlie the higher Vs top layers at the northern and southern flanks of the profile. The profile also shows lateral velocity variation at depths below the low velocity second layer, with velocity increasing above $530ms^{-1}$ at a depth of between 85-110m at the central region while at the flanks; this high Vs feature is underlain by lower Vs layers. The Vs model obtained for receiver line 7 shows a 10-15m thick low shear wave velocity (250-$300ms^{-1}$) second layer that stretches from the southern flank of the profile grading to the surface towards the north at receiver location 153000. This low velocity layer continues at the surface with a thickness of about18m to the 156000 receiver point from where it again underlies a higher velocity layer at the northern end of the profile. Beneath this low Vs second layer, Vs increases steadily down to the half space only for the edge of the northern flank. From the 156000 receiver point to the south, several velocity reversals are observed as well as the undulating disposition of the layers.

DISCUSSION

The shear wave velocity profiles obtained in this field exhibit a specific pattern of shear wave velocity distribution. Considering profile lines in descending order, starting from the south of each profile line, it is observed that a low velocity layer underlying a relatively higher velocity first layer, extends towards the north and begins to expand in thickness upwards, till it truncates the higher velocity first layer, to outcrop at the surface around the central regions of the profile lines. After some distance, this low velocity feature thins out again to underlie the first layer of higher velocity at the northern edge of the profiles. This pattern is seen to be continuous on the 7^{th}, 6^{th}, 5^{th} and 4^{th} receiver line profiles. The other profile lines (3-1) slightly vary from this distribution pattern, having this low velocity layer occurring at the surface for some of them. However, this gives the geometrical distribution of the low velocity layer (LVL) in the field.

Based on the velocities observed, the depth to consolidated sediment in this field, approximately range between 10 to 30m. Furthermore, the low shear wave velocities of the top soils, coupled with the velocity reversals observed suggest that surface waves are bound to dominate seismic reflection data, if shot holes are not placed deep enough to avoid these LVL, which would serve as wave guides for their propagation. Figure 5 is the map of the top of the consolidated layer. This figure shows that for efficient penetration of seismic energy, the shots should be planted at depth ranges of about 10 - 30m. It should be noted that the deeper depths of the LVL encountered occur at locations where low velocity layers are sandwiched between the surface layers and the deeper consolidated sediments. These zones occur mainly in the northern third of the study area and trending south-east from the middle of the area. There is a general lateral variability of velocity along all the profile lines especially below the near surface low velocity layer. It is also interesting to note the observation of pockets of higher velocity materials at depths of about 75-95m within the profile lines. This pattern of localized high velocity sections will also contribute to different seismic problems during data acquisition. These highly resolved velocity distribution maps resulted from the use of multimodal analysis of surface waves. Further analysis of this observed localized high velocity features at depth should be carried out to determine the source of these geologic structures and their effects on both incident and transmitted rays, most probably using ray tracing technique.

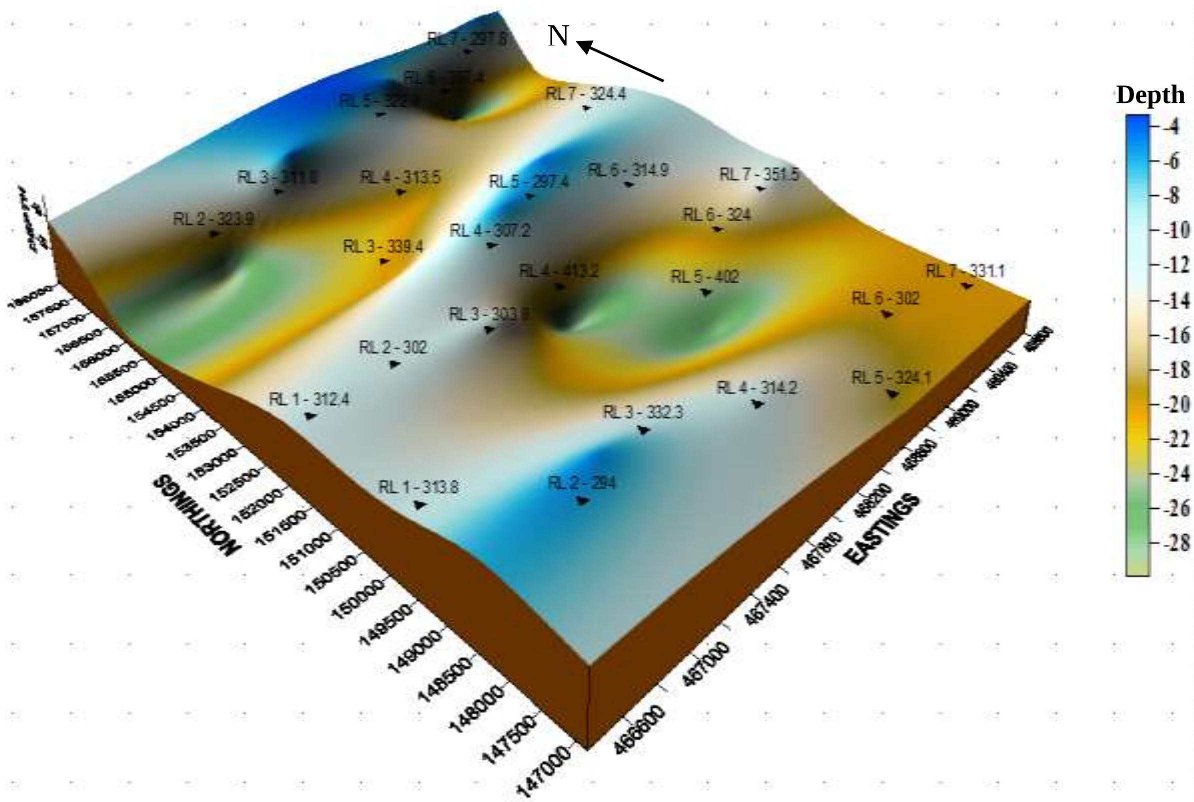

Figure 5: Surface map view of the depth of the consolidated sediments which we interpret for the location of seismic sources for effective and efficient seismic energy penetration. The shaded colours represent the depth to the top of the consolidated sediment while the diamonds and the numbers are the receiver line numbers with the values of the shear velocities at their locations.

CONCLUSION

Through the application of the MASW technique, the shear wave velocity and by implication the rigidity modulus of the shallow subsurface of an SPDC 'X' field in the Niger delta region has been accurately mapped. The results show that surface waves were excited within the top 10 – 28 m low velocity zone. This surface low velocity layer and the intermediate underlying velocity reversals contribute to the excitation of surface waves. This surface wave excitation traps the seismic energy needed for deeper penetration especially when we consider that surface waves have more of the low frequencies needed for deep penetration.

Based on the velocity distribution observed, the depth to the consolidated sediments where shots can be planted during seismic acquisition in the field, for efficient seismic energy penetration, approximately range between 10m to 30m. The deepest zones occur where the low velocity layers occur between the surface layer and the consolidated sediment. The profiles also show that the shallow subsurface in this field exhibit some structural variability, which may be considered as expressions of deeper seated structural features; although we consider that if our lateral and vertical resolutions are optimally improved, we may better resolve these features.

Acknowledgement

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