

Full Length Research Paper

Investigation into the weathering layer using up-hole method of seismic refraction

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This paper is aimed at using up-hole method of seismic refraction survey to investigate the thickness of the weathering layer as well as the velocity of seismic waves through the layer. The first events to arrive at the geophones on a refraction profile had travelled by refraction along the top of the high speed zone just below the weathering layer. Using the time- offset curves of the first arrivals for shots from different charge depths; the thickness of the weathering layer was calculated by conventional seismic refraction methods. Such a survey was carried out using a TD500 top drive drilling machine mounted on a 6 × 6 m truck. The depth of the weathering layer as well as the velocities of seismic waves in the weathering layer and the refractor, were calculated from critically refracted arrivals using flat layer models. Using the time-intercept method for interpretation, the thickness of the low velocity weathering layer in the area varied from 15 to 20 m with a regional average of 18.15 m. The p-wave velocity in the uppermost layer varied from 1385 to 800 m/s with an average value of 1092 m/s. This is a direct experimental proof of low velocity zone confirming the weathered nature of the area.

Key words: Up-hole survey, seismic refraction, p-wave velocity, weathering layer, consolidated layer.

INTRODUCTION

The up-hole method of seismic refraction survey is a field seismic technique which uses receivers on the ground surface and an underground source to derive information about the subsurface lithology.

The up-hole survey method uses small explosives or a mechanical source (energy source). This method is used to obtain seismic data in areas where the thickness or velocity in the weathering layer vary considerably. The problem of weathering layer which absorbs seismic waves during conventional seismic refraction experiment is solved using this method of survey. The hidden (low velocity zone - LVZ) layer can of course be detected by shooting from a borehole to the seismic spread geophones Dobrin (1983).

The advantage is that signal paths are much shorter, that is, from borehole to the ground surface rather than

down from the surface and back up again. The shorter signal path means that each signal samples a smaller volume of the subsurface materials (creating a higher resolution images) and suffer lesser signal loss (creating the ability to image subtle targets).

Study area

Location

The area under study is the northeast of Niger Delta in the southwestern part of Nigeria. The Niger Delta is located between longitude 4° to 9°E and latitude 4° to 6°N (Figure 1).

Geology

The area is part of the Niger Delta complex. The sediments are unconsolidated and have a highly variable

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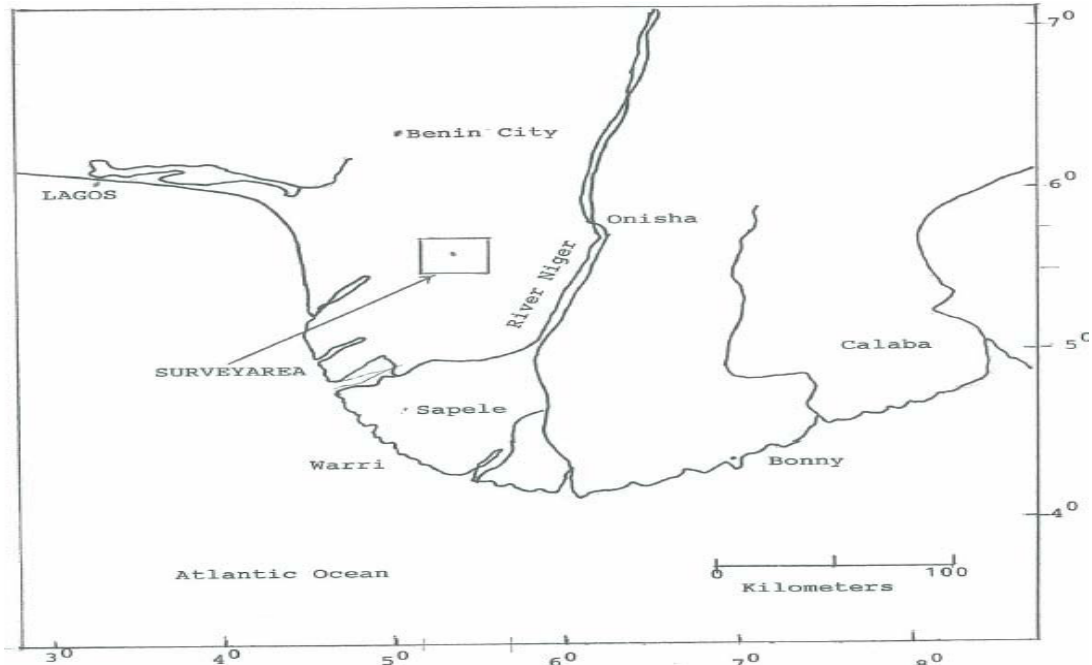


Figure 1. Southern Nigeria showing the Niger Delta Region and the study area.

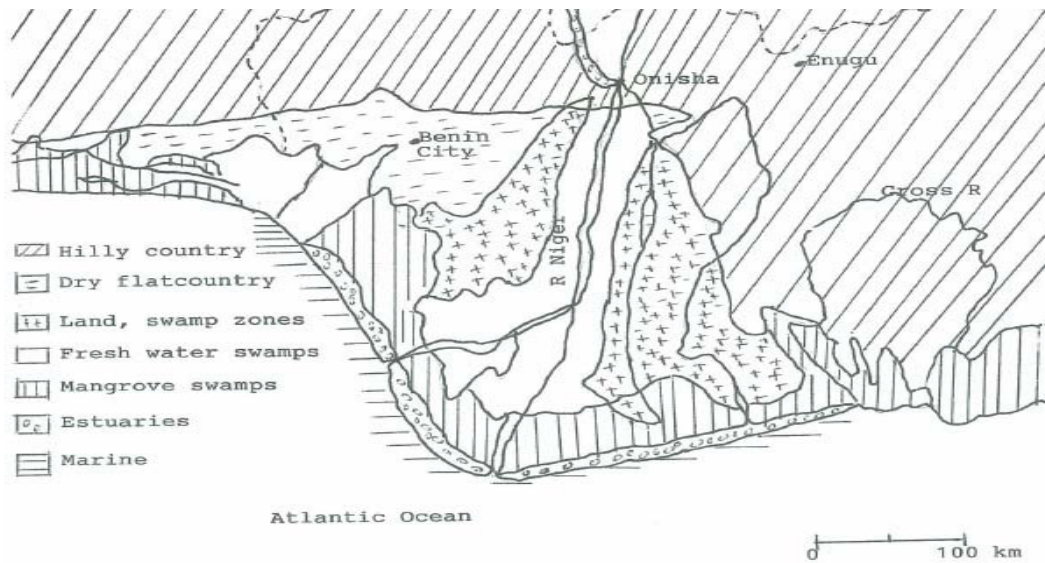


Figure 2. Geological features and sedimentary environment of the Niger Delta.

thickness throughout the region. It is made up of fresh water swamps and mangrove swamps with relief that increases towards the north.

Niger delta is characterized by both marine and mixed continental depositional environment which is believed to have originated during the Eocene era (Aseez, 1976; Kogbe, (1976)). The Niger Delta is composed of three sedimentary formations, namely the Benin, the Agbade, and Akata Formations Hospers, (1965). The Benin

Formation consists of coarse – grained, gravelly sandstones with minor intercalations of shale. It is a continental deposit of Miocene to younger age and has a thickness in excess of 1800 m. Typical outcrops of the Benin Formation can be seen around Benin, Onitsha, and Oban where this survey was carried out (Figure 2).

The Agbada Formation consists of alternating sandstone and shale and is fluviomarine in origin. It is Eocene in age in the north and Pliocene in the south.

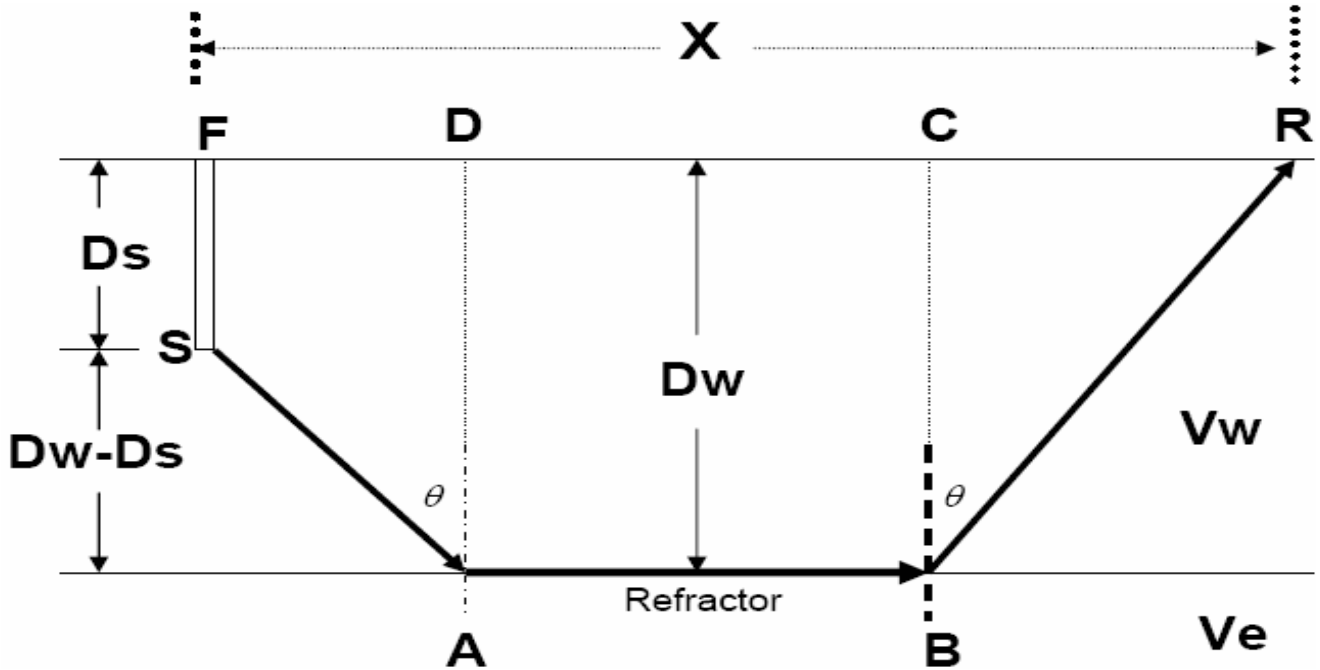


Figure 3. Shot in the weathering layer.

These sands, sandstones and marine shale which make up the Agbada Formation has a maximum thickness of about 4600 m. The Akata Formation consists of shale with local interbedding of sands and siltstones (Igboekwe et al., 2008).

The major aims and objectives of this paper therefore are to investigate the thickness of the weathering layer and to determine the propagation velocity in the weathering layer.

Because the Niger Delta is characterized by fault bounded sedimentation, extensive shale structure and weathered layers which comprise of low velocity zones/layers Osagie (2009), the conventional near surface seismic refraction method will not yield a highly reliable result due to the low velocity layers associated with weathered layers. Hence a better approach such as the up-hole method of seismic refraction survey, if applied here, guarantees a better image of the subsurface lithology.

Travel time equations and their specifications

Three special cases of travel time equations are considered as shown below:

Shot in the weathering layer ($D_w > D_s$)

Consider a single shallow shot taken at a depth D_s (within the weathering layer, that is, $D_s < D_w$) where D_w is the thickness of the weathering layer (Figure 3).

The total travel time T between the shot instant at S and receiver at R is given by

$$T = T_{SA} + T_{AB} + T_{BR} \tag{1}$$

$$T = \frac{SA}{V_w} + \frac{AB}{V_e} + \frac{BR}{V_e} \tag{2}$$

where V_w is the velocity in the weathering layer and V_e is the velocity in the consolidated layer.

$$T = \frac{D_w - D_s}{V_w \cos \theta} + \frac{AB}{V_e} + \frac{D_w}{V_w \cos \theta} \tag{3}$$

where θ is the critical angle of incidence.

Now,

$$AB = x - (FD + CR) \text{ and } \frac{FD}{D_w - D_s} = \tan \theta \tag{4}$$

Therefore,

$$FD = (D_w - D_s) \tan \theta \tag{5}$$

Similarly,

$$\frac{CR}{D_w} = \tan \theta,$$



Figure 4. T-X plot for a 2-layer case.

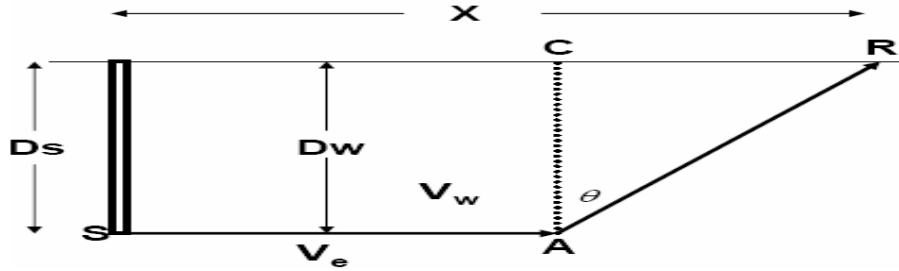


Figure 5. Raypath for shot at base of weathering layer.

so that

$$CR = D_w \tan \theta \quad (6)$$

Hence,

$$AB = \chi - [(D_w - D_s) \tan \theta] - D_w \tan \theta = \chi - (2D_w \tan \theta - D_s \tan \theta) \quad (7)$$

Therefore, the travel time equation becomes

$$T = \frac{D_w - D_s}{V_w \cos \theta} + \frac{\chi - (2D_w \tan \theta - D_s \tan \theta)}{V_e} + \frac{D_w}{V_w \cos \theta}$$

$$= \frac{\chi}{V_e} + \frac{2D_w}{\cos \theta} \left[\frac{1}{V_e} - \frac{V_w}{V_e^2} \right] - \frac{D_s}{\cos \theta} \left[\frac{1}{V_w} - \frac{V_w}{V_e^2} \right]$$

Therefore,

$$T = \frac{\chi}{V_e} + \frac{2D_w (V_e^2 - V_w^2)^{1/2}}{V_e V_w} - \frac{D_s (V_e^2 - V_w^2)^{1/2}}{V_e V_w} \quad (8)$$

The weathering thickness is obtained from Equation 8 by setting the offset to zero. That is, $\chi = 0$. At zero offset, the total travel time, $T = T_i$ where T_i is the intercept time. From Equation 8, we have that

$$T_i = \frac{2D_w (V_e^2 - V_w^2)^{1/2}}{V_e V_w} - \frac{D_s (V_e^2 - V_w^2)^{1/2}}{V_e V_w} \quad (9)$$

From this the weathering thickness can be obtained as

$$D_w = T_i \frac{V_e V_w}{2(V_e^2 - V_w^2)^{1/2}} + \frac{D_s}{2} \quad (10)$$

From Snell's law,

$$\cos \theta = \left(1 - \frac{V_w^2}{V_e^2}\right)^{1/2}, \text{ and } \frac{1}{\cos \theta} = \frac{V_e}{(V_e^2 - V_w^2)^{1/2}} \quad (11)$$

Hence,

$$D_w = \frac{T_i V_w}{2 \cos \theta} + \frac{D_s}{2} \quad (12)$$

The T-X plot for the above case is shown in Figure 4.

Shot at the base of the weathering layer ($D_s = D_w$)

The total travel time T for this case (Figure 5) is given by:

$$T = T_{SA} + T_{AR}$$

$$= \frac{SA}{V_e} + \frac{AR}{V_w} \quad (13)$$

Therefore,

$$T = \frac{\chi - D_w \tan \theta}{V_e} + \frac{D_w}{V_w \cos \theta}$$

$$= \frac{\chi \cos \theta - D_w \sin \theta}{V_e \cos \theta} + \frac{D_w}{V_w \cos \theta} \quad (14)$$

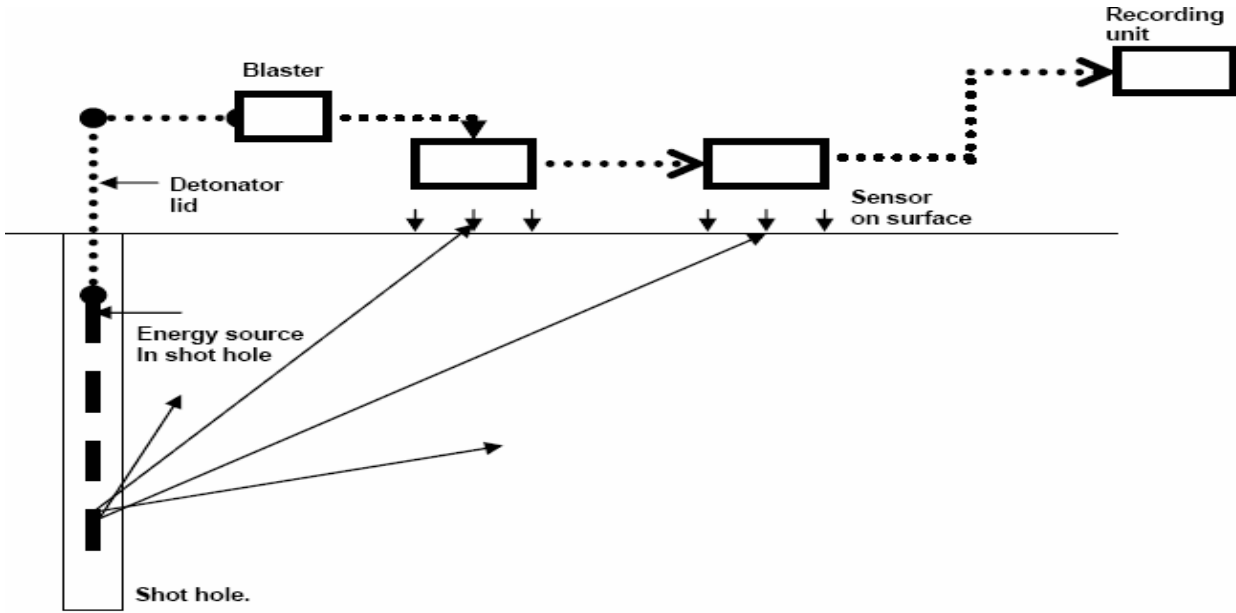


Figure 6. Field layout for Up-hole survey data acquisition.

Following the same procedure, we have that;

$$T = \frac{x}{V_s \cos \theta} + \frac{D_w (V_s^2 - V_w^2)^{1/2}}{V_s V_w} \quad (15)$$

At $X=0$, $T = T_i$. So that, $T_i = \frac{D_w (V_s^2 - V_w^2)^{1/2}}{V_s V_w}$ (16)

Therefore, the weathering thickness is obtained as:

$$D_w = \frac{T_i V_s}{\cos \theta} \quad (17)$$

Shot taken in the consolidated layer ($D_s > D_w$)

In practical field situation, the direct arrival curve from which the first velocity is determined disappears when the shot is below the weathering layer. This makes it impossible to determine the weathering thickness for any shot taken below the weathering layer.

DATA ACQUISITION AND METHODOLOGY

In the up-hole survey, a deep hole is drilled at the intersection of source and receiver line in a seismic refraction data acquisition project. In this procedure, dynamite charges are laid successively in the hole at intervals starting from the deepest depth level of interest, each charge having a detonator lid extending to the surface with the depth written on it.

The hole is tamped after each shot is laid to prevent loss of energy up the hole when a shot is taken. Therefore, a number of geophones are laid on the surface at respective intervals from the hole. At the end of the shooting, a single geophone jug is planted

near the surface very close to the hole and a shot taken with a detonator cap planted near the surface in the hole. The idea is to obtain an up-hole pre-trigger time, which is the time that would elapse between the initiation of a shot and its reception by a geophone. Figure 6 is a sketch of the field arrangement for the data acquisition (Ogagarue, 2007).

Data processing

After a shot is taken, a plot of arrival times versus geophone offset is made on a monitor record and this constitutes the data set (Table 1). In processing of the data, first-break arrival times are picked for various shots. First-break time is the first pick-up time recognized for any trace, and is the parameter of interest in the interpretation of up-hole survey data.

The up-hole survey data are normalized by subtracting the pre-trigger time from the first-break time. By this, it is assumed that the pick-up time of a shot by each geophone is the same; therefore, differences are due to time delays introduced into the data by the weathering layer. Near to surface depth models are computed from picked first to break time; and to achieve this, a plot of the corrected time is made against each channel for every shot in the up-hole survey method. From this, it is seen that the depth of the weathering layer computation is based on the zero to offset time which is obtained by extrapolating the refraction curve to the time axis.

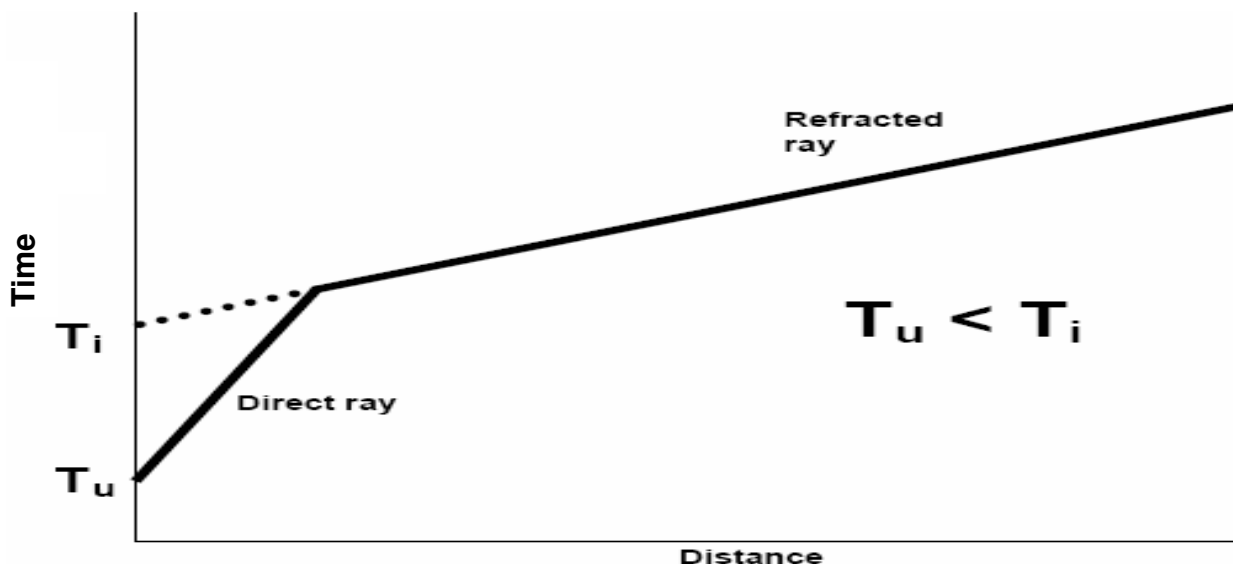
Data interpretation

Normally in the interpretation of the up-hole survey data, computation of the weathering depth is a function of the plot in question. If the plot is such that the up-hole time is less than the intercept time (Figure 7); it implies that the shot is in the weathering layer and Equation 12 may be sufficient in determining the weathering thickness. On the other hand, as shown in Figure 8, when the intercept time is less than the up-hole time, the curve is no longer that of refraction but reflection, and the inverse slope gives the velocity in the consolidated layer. The implication here is

Table 1. First- break listing for up-hole data.

No. of traces	Offset (m)	Charge depths (m)											
		10	15	20	25	30	35	40	45	50	55	60	65
Arrival times for various charge depths (ms)													
1	1	10.9	13.4	18.7	19.8	20.9	21	22.3	23.4	24.4	25	27	30.2
2	3	14.9	17.4	16	14.9	20.8	21.2	22.4	23.4	24.3	25.2	27	30.3
3	5	16.9	20	19.9	20.5	22	22.5	22.5	24.4	25	27.5	28	30.5
4	8	17.9	22	20.9	22	22.9	23.4	24.5	25.2	26.4	28.5	28	30
5	10	18.9	25	22.9	27	23.9	25	25	25.9	27	30.5	30.2	32
6	13	20.5	28	24.4	30	25.4	27	25.7	27.3	28	34.2	32	35.2
7	25	24.5	29.5	25.9	32	26.5	27.2	28	30	30	36.4	35.2	35.5
8	35	25.5	32	27.9	32.2	27	28.5	30.5	32	34.9	38	35.2	36.5
9	45	33	35	31.4	33	30.5	30.3	32.5	37.5	37	39	35.5	37.6
10	55	35	37	34.5	38	33.7	33.9	34.5	37.6	37.2	39.4	36.5	38.9
11	65	37.5	39	38	39	37.5	37	36	38	38.5	39.5	37.6	38.5
12	80	42	40	40.2	39.5	38.9	39.5	38.9	38.7	39	39.5	39.5	39.5

Adapted from ELF Nigeria Limited.

**Figure 7.** T-X plot for shot taken in the weathering layer.

that the shot is at the base of the weathering layer or within the consolidated layer. Here, the ray's path crosses the weathering layer only once and the weathering depth can be computed from Equation 17.

However, at some shot depths the up-hole and intercept times would be approximate. This immediately gives the clue to the depth of the weathering layer because the shot depth at this instant is close to the base of the weathering.

RESULTS AND DISCUSSION

A quantitative interpretation of the up-hole survey data shows that for $D_s \geq 20$ m, the up-hole time is greater than the intercept time whereas, for $D_s = 10$ m and $D_s = 15$ m,

the converse is the case [Figure 9(a - l)]. This immediately indicates that the base of the weathering layer is between 15 and 20 m.

For $D_s = 10$ m

$$\frac{1}{V_w} = \frac{(19-12.5)10^{-3}}{(10-1)} = 0.722 \times 10^{-3}$$

or

$$V_w = 1384.62 \text{ m/s}$$

and error,

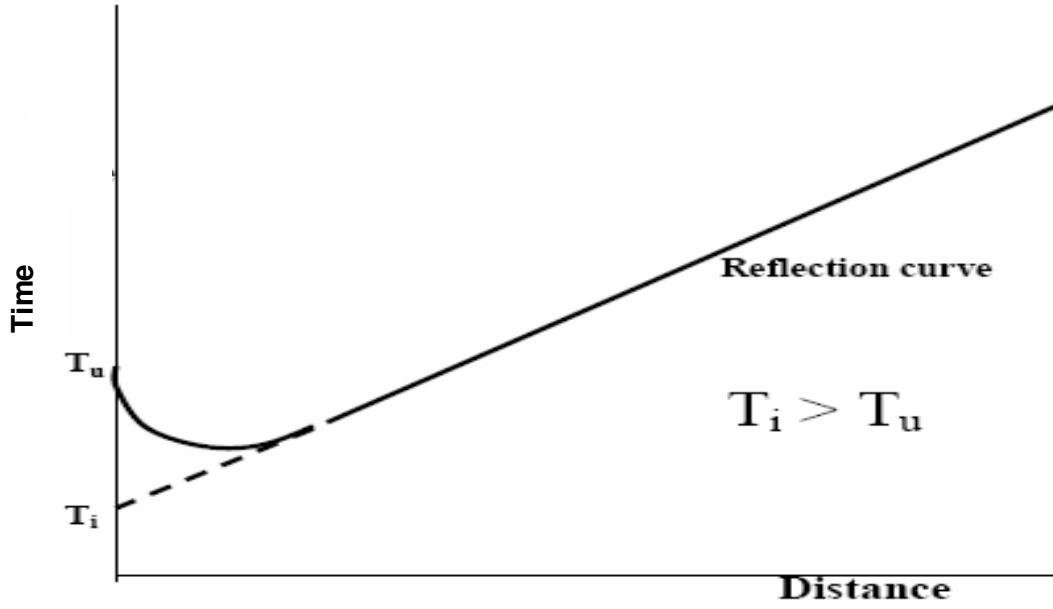
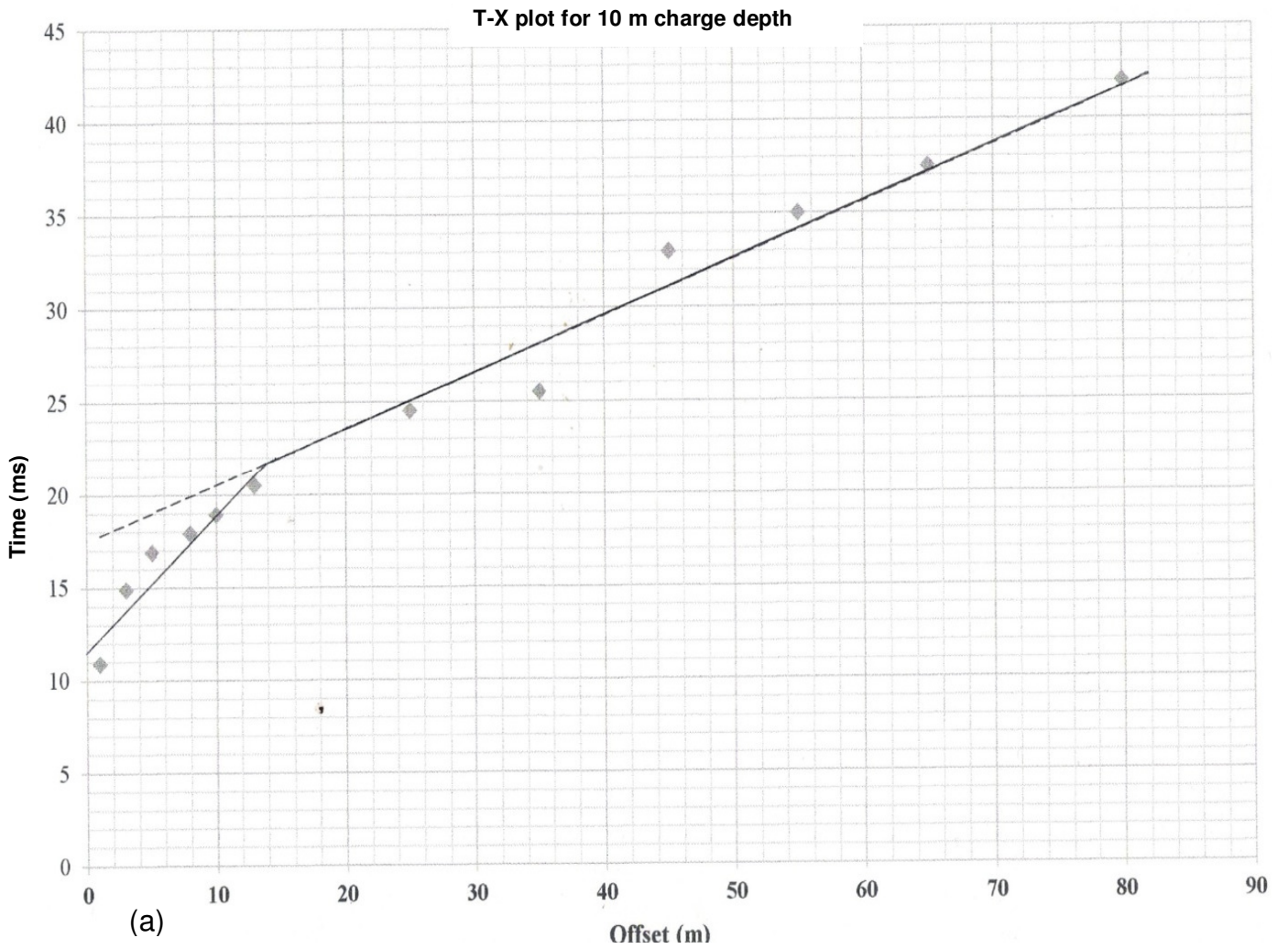
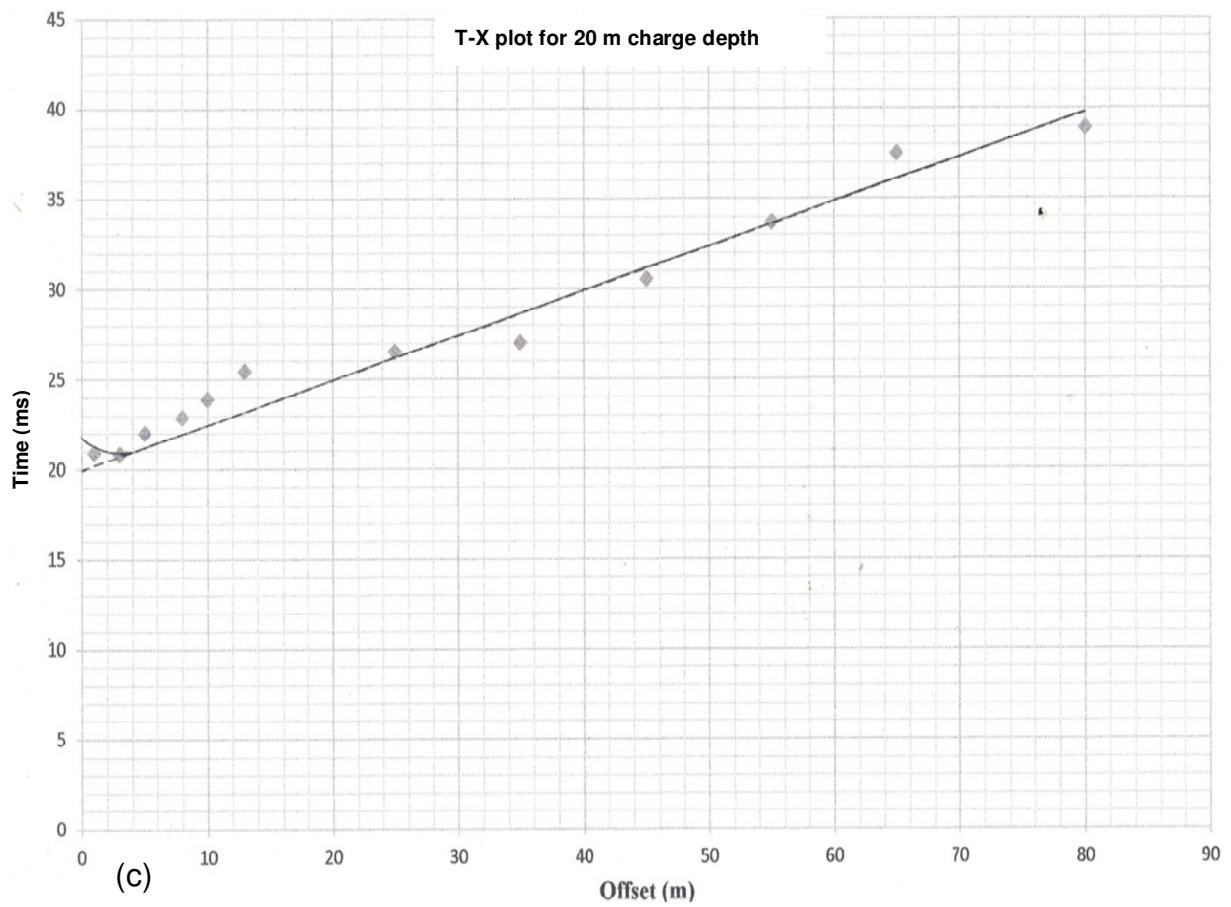
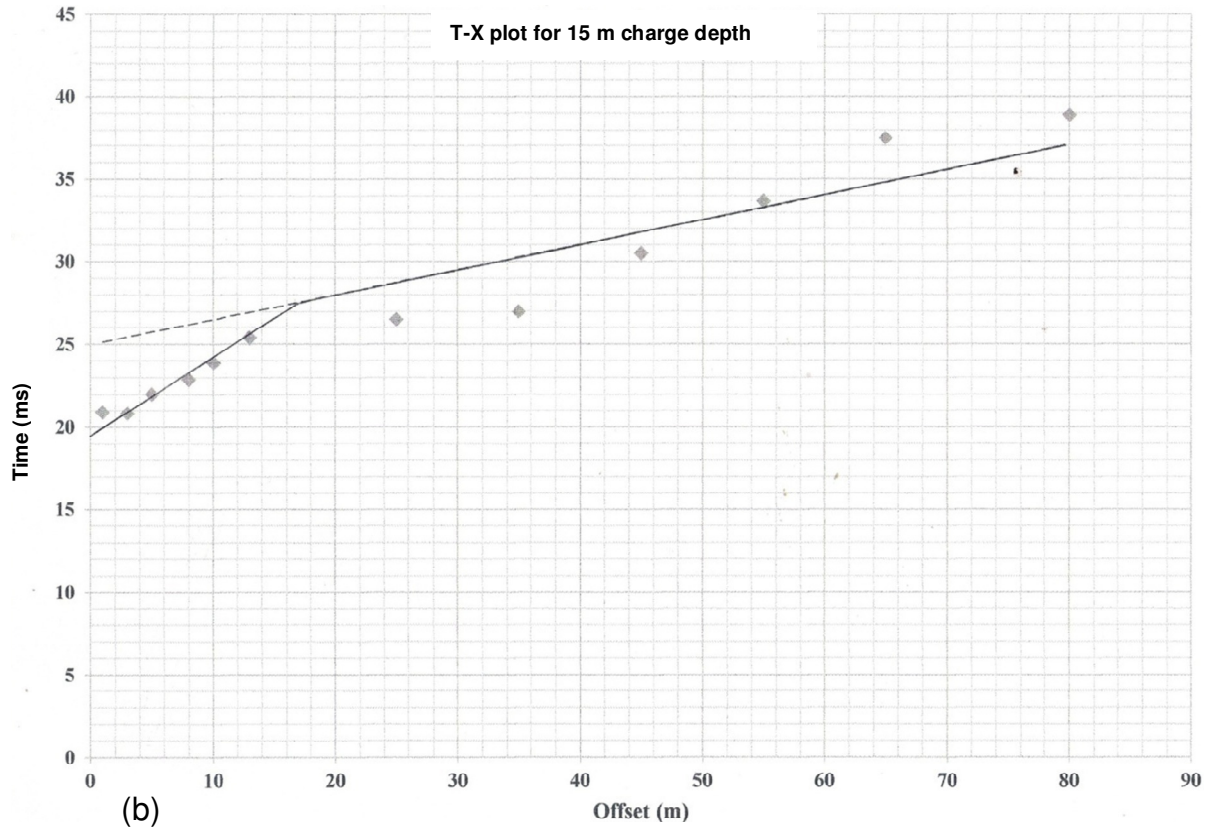
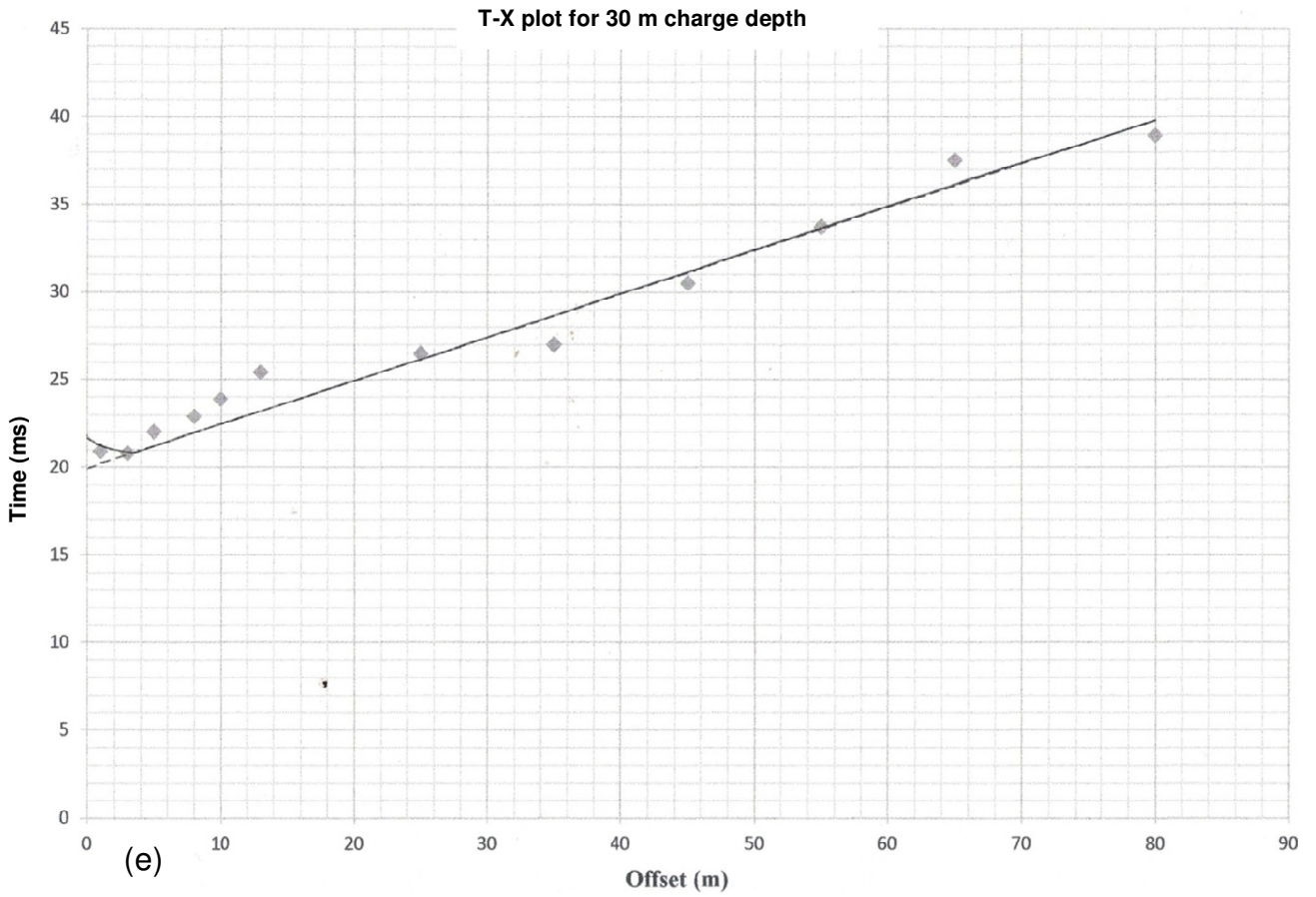
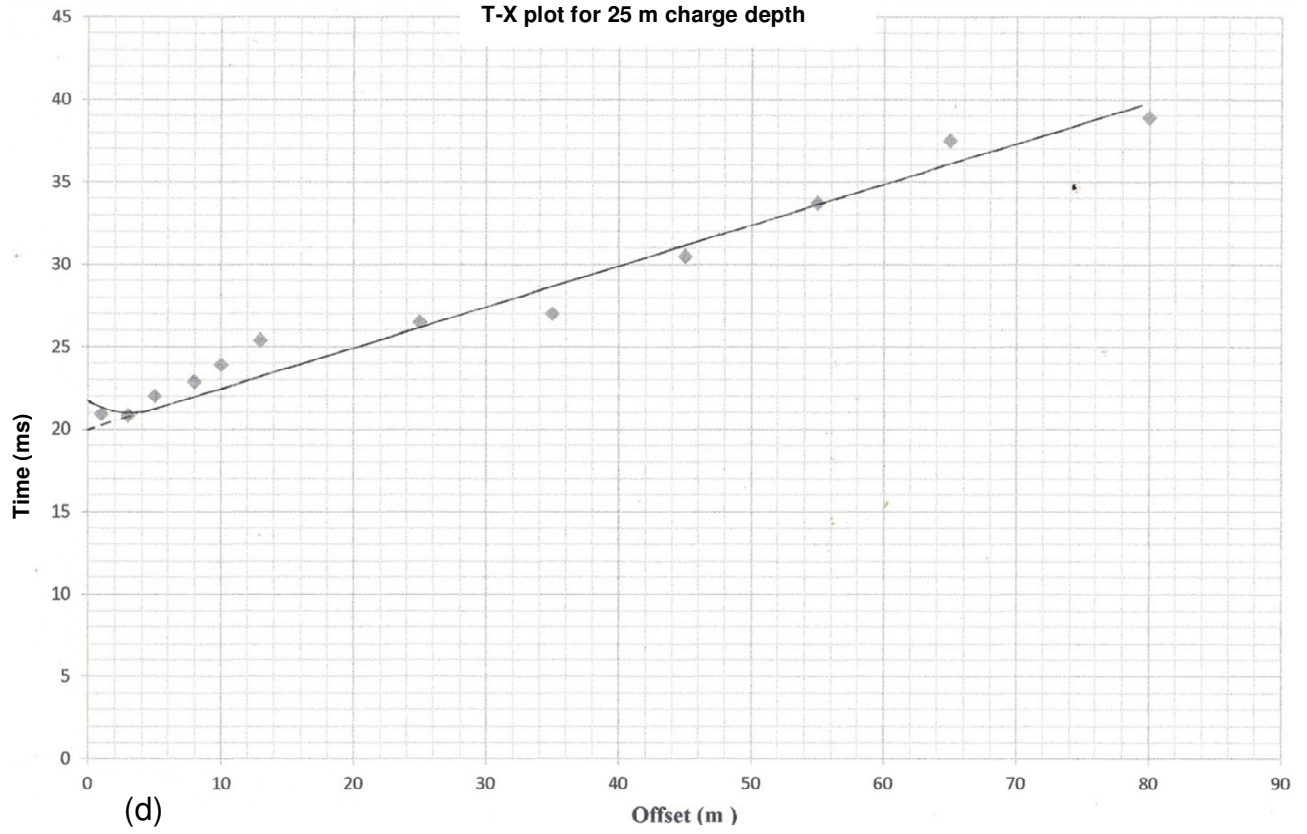
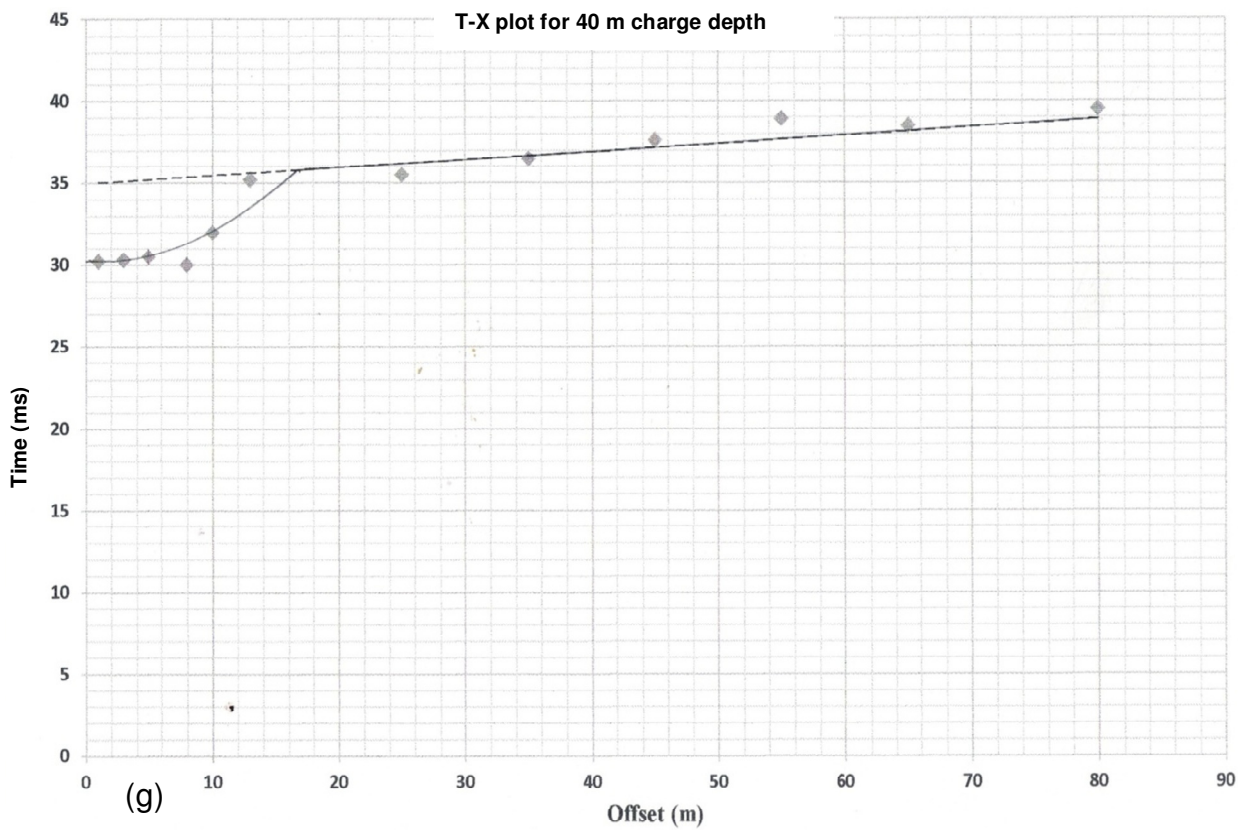
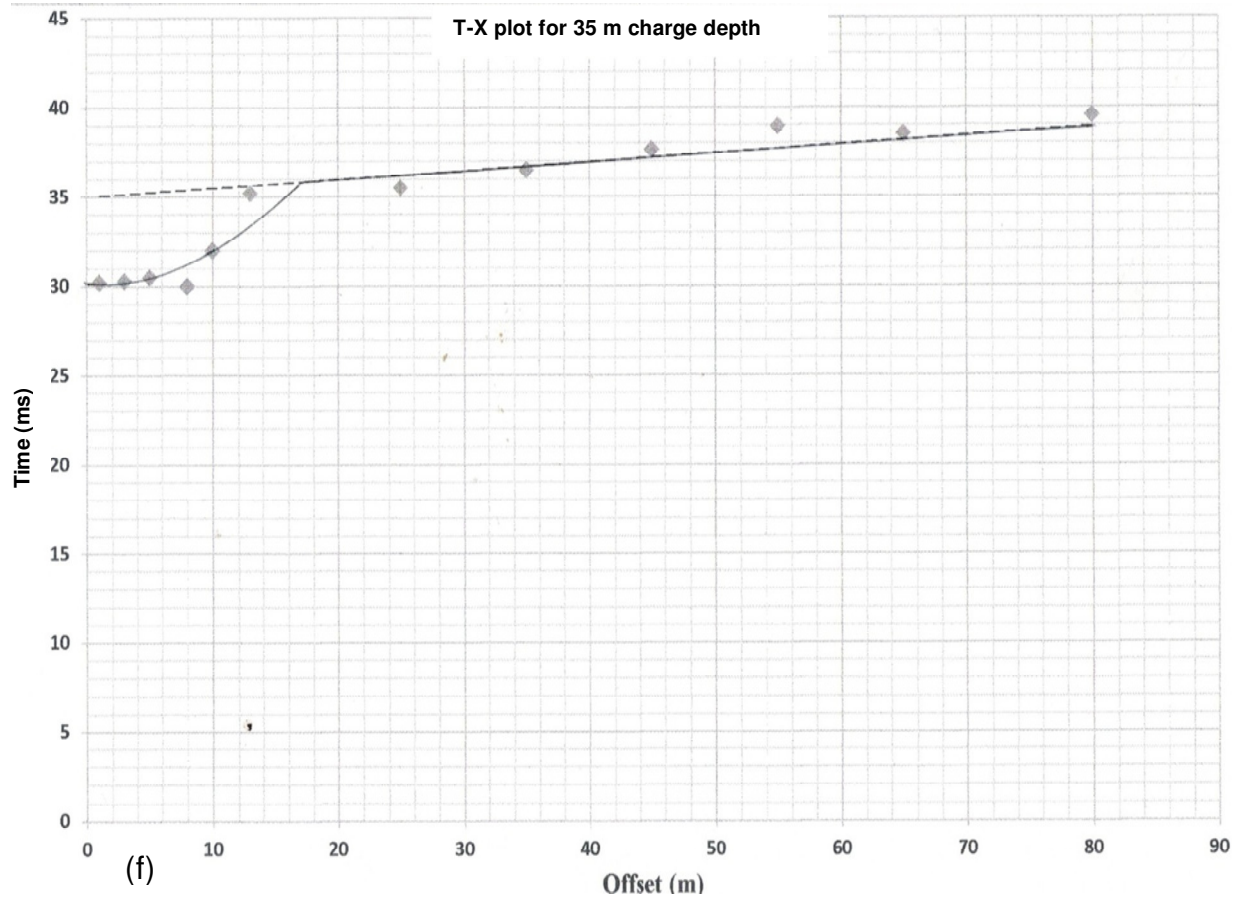


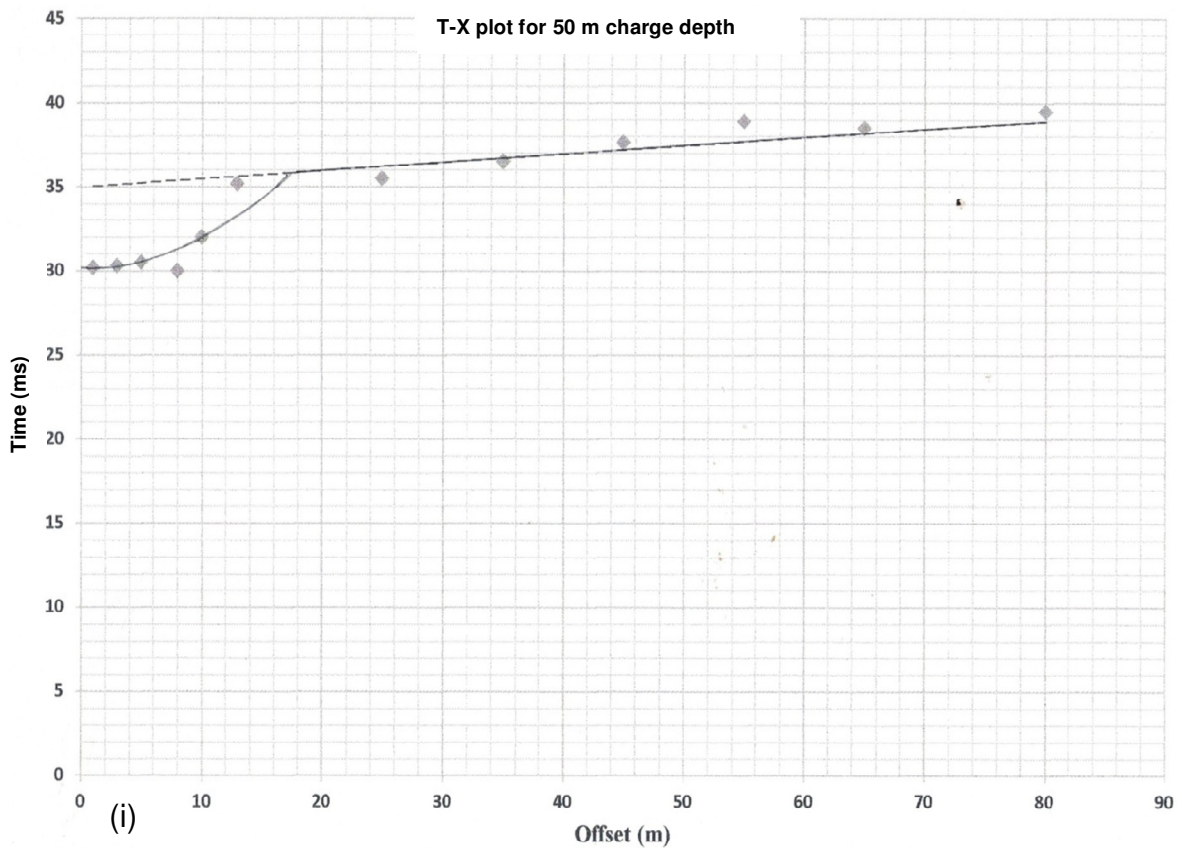
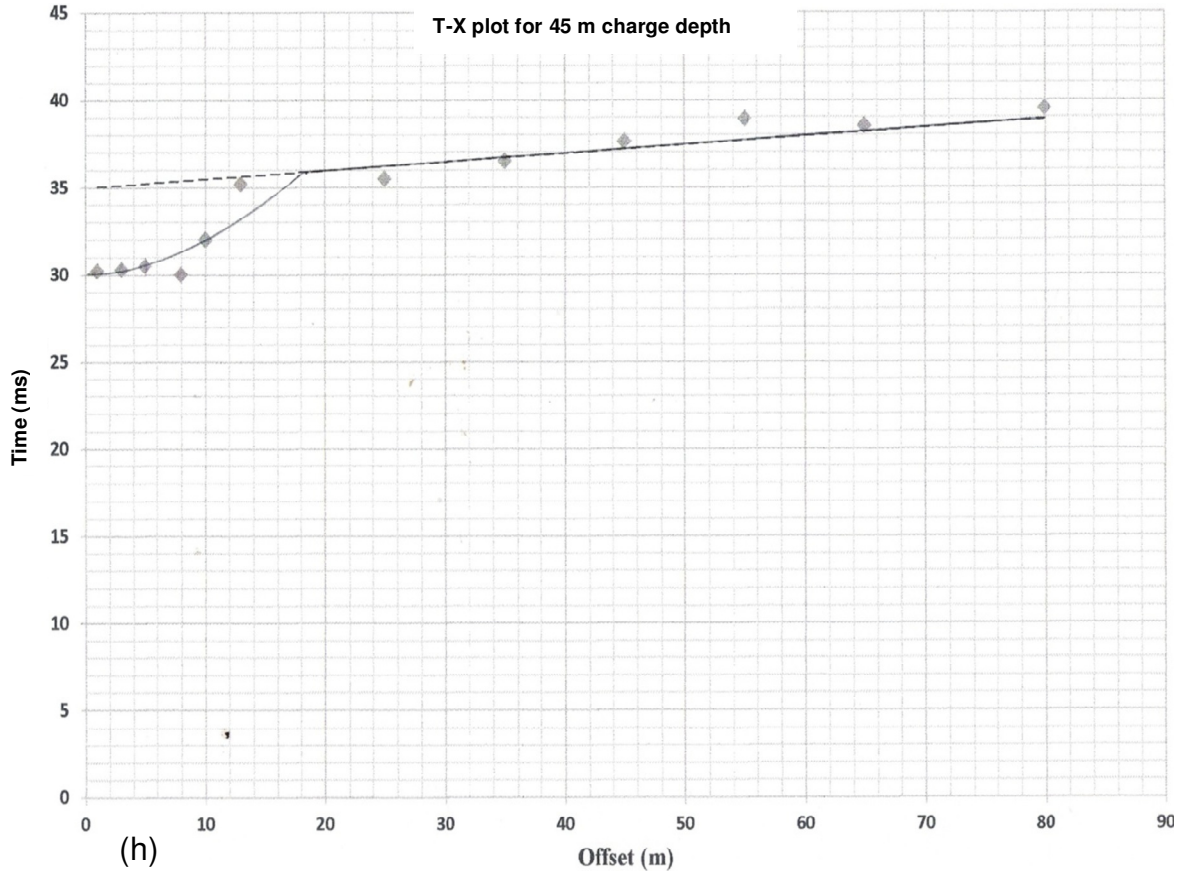
Figure 8. T-X plot for a shot within the consolidated layer.

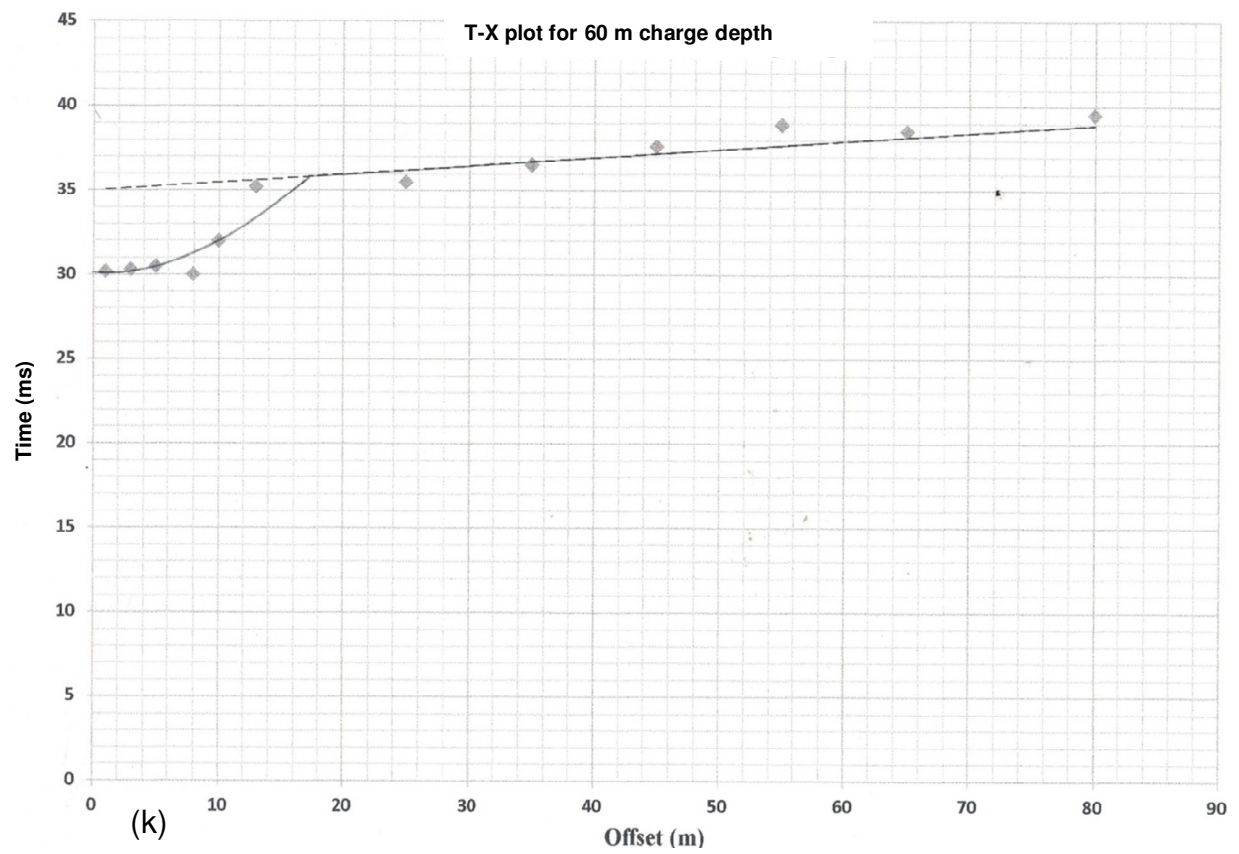
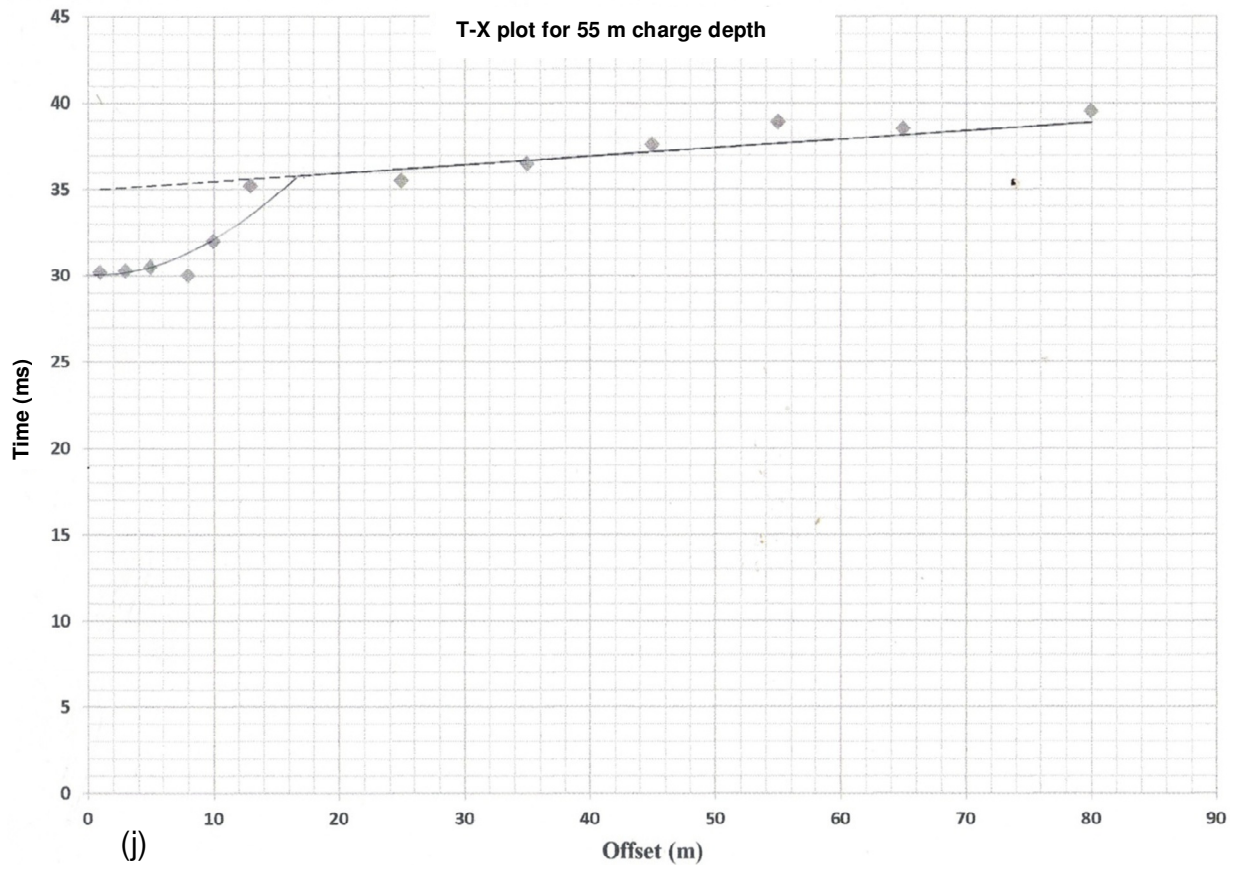












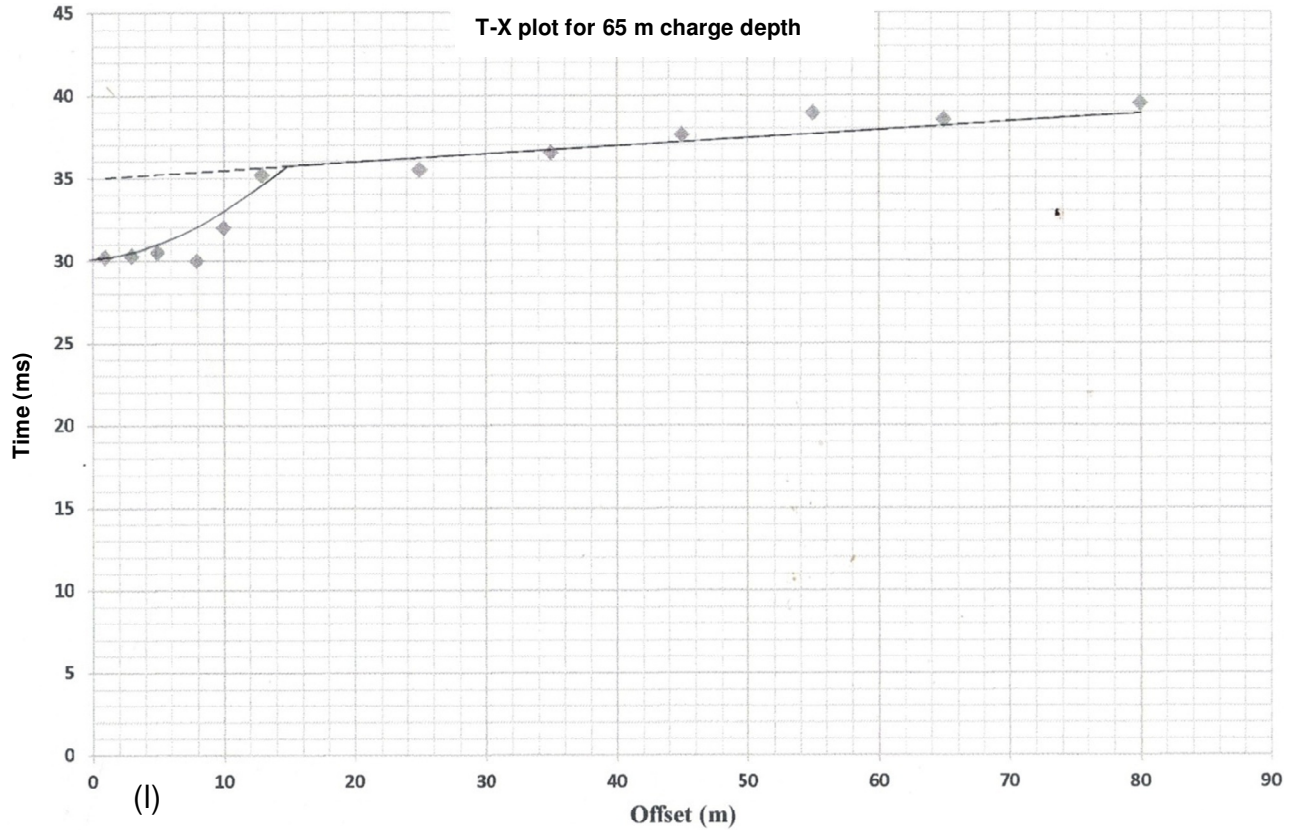


Figure 9. T-X plots for various charge depths: (a) 10 (b) 15 (c) 20 (d) 25 (e) 30 (f) 35 (g) 40 (h) 45 (i) 50 (j) 55 (k) 60 (l) 65.

$$E_w = \frac{4w}{mR} = \pm 0.25$$

Hence, the weathering layer velocity,

$$V_w = 1384.62 \pm 0.25 \text{ m/s.}$$

$$\frac{1}{V_e} = \frac{(39.25 - 25)10^{-3}}{(70 - 25)} = 3.1667 \times 10^{-4}$$

or

$$V_e = 3157.89 \text{ m/s}$$

and error,

$$E_e = \frac{4w}{mR} = \pm 0.06$$

Hence, the consolidated layer velocity,

$$V_e = 3157.89 \pm 0.06 \text{ m/s}$$

From Equation 12,

$$D_w = \frac{T_i V_w}{2 \cos \theta} + \frac{D_s}{2},$$

$$T_i = 17.5 \text{ ms}$$

$$\cos \theta = \left(1 - \frac{V_w^2}{V_e^2}\right)^{1/2} = \left(1 - \frac{1384.62^2}{3157.89^2}\right)^{1/2} = 0.898749$$

Therefore,

$$D_w = \frac{1384.62 \times 17.5 \times 10^{-3}}{2(0.898749)} + \frac{10}{2} = 18.48 \text{ m}$$

For 15 m charge depth

$$\frac{1}{V_w} = \frac{(25 - 15)10^{-3}}{(10 - 2)} = 1.25 \times 10^{-3}$$

or

$$V_w = 800 \text{ m/s}$$

and error,

$$E_w = \frac{4w}{mR} = \pm 0.15$$

Hence,

$$V_w = 800.00 \pm 0.15 \text{ m/s}$$

$$\frac{1}{V_e} = \frac{(39-30)10^{-3}}{(70-23)} = 0.191 \times 10^{-3}$$

or

$$V_e = 5222.22 \text{ m/s}$$

and error,

$$E_e = \frac{\Delta V}{VR} = \pm 0.03$$

Thus,

$$V_e = 5222.22 \pm 0.03 \text{ m/s}$$

Using Equation 12;

$$D_w = \frac{T_i V_w}{2 \cos \theta} + \frac{D_s}{2}$$

or

$$T_i = 25.5 \text{ ms}$$

$$\cos \theta = \left(1 - \frac{V_w^2}{V_e^2}\right)^{1/2} = \left(1 - \frac{800^2}{5222.22^2}\right)^{1/2} = 0.988$$

Therefore,

$$D_w = \frac{800 \times 25.5 \times 10^{-3}}{2(0.988)} + \frac{15}{2} = 17.82 \text{ m}$$

Average weathering velocity, $\langle V_w \rangle = 1092.31 \text{ m/s}$

Average weathering thickness, $\langle D_w \rangle = 18.15 \text{ m}$

Average velocity in consolidated layer, $\langle V_e \rangle = 4190.06 \text{ m/s}$.

These values agree, giving an average weathering thickness of 18.15 m; this agrees well with the quantitative interpretation of the data. Also, the decrease in the weathering layer velocity from 1385 to 800 m/s clearly indicates the low velocity zone associated with weathering layers.

Conclusion

Up-hole method of seismic refraction as we have seen has been used in finding the velocity as well as the thickness or depth of the weathering layer in this study

area. This has proved the method to be an invaluable tool in hands of geophysicists in overcoming the problem of low velocity associated with weathering layers which is a limiting factor in conventional seismic refraction method.

The information obtained from this study is extremely important in the determination of time delays needed for static corrections during seismic reflection data processing. This is because of the need to know the depth of the base of weathering layer before a seismic reflection survey, which helps to locate the energy source at appropriate depth so as to reduce the ground roll that will interfere with the seismic reflection data. Besides that, the energy transmitted into surface can be maximized by placing the source below the weathered zone.

From the analysis carried out here, up-hole survey method of seismic refraction has revealed that the uppermost layer has an average thickness of about 18.15 m and the decrease in velocity from 1385 to 800 m/s with an average p – wave propagation velocity of 1092 m/s clearly indicates that the area is highly weathered with associated low velocity zone.

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