ABSTRACT

Aim: Computer software was developed for seismic refraction data interpretation and computation of engineering parameters as a means to ease the problem of cumbersomeness of the manual interpretation of seismic refraction data and computation of engineering parameters by adopting seismic refraction method of investigation.

Study Design: Software development.

Place and Duration of Study: Department of Applied Geophysics, Federal University of Technology, Akure, Ondo State, Nigeria, between June 2010 and February 2011.

Methodology: Necessary equations for the program were compiled, and the program algorithms were developed, fed into a computer interpreter, debugged and run. The program algorithm was written with Visual Basic Programming Language and the software was designed using Visual Basic tools.

Results: The software accepts and interprets Single On Shot and On and Reverse Shot seismic refraction data for planar and dipping interface. The developed software plots T-X graph and compute the layer velocities and thicknesses. Engineering parameters such as Fracture Frequency (n), Rock Quality Designation (RQD), Bulk and Young modulus and Poisson ratio (σ) which are used in subsurface engineering evaluation can also be computed using the software.

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Conclusion: Seismic refraction data for both planar and dipping interface were obtained and used in testing the efficiency of the software and the results correlate with that of manual interpretation and computation.

Keywords: Computer software; seismic refraction; visual basic programming language; engineering parameters.

1. INTRODUCTION

With the recent development in the world of Information Technology (IT), it becomes pertinent to improve on the manual routine of processing and interpreting data. It was observed that in the field of engineering geophysics which usually involves the use of Seismic Refraction and Electrical Resistivity as primary geophysical methods, computer program has not been largely documented in the geophysical literatures; developed for the estimation of engineering parameters using seismic refraction data.

Seismic theory is believed to be originated from the knowledge of the principles of light and sound in physics. Therefore, the need for the understanding of the behavior of waves in the subsurface paved way for its study and the application of these principles into the subsurface, resulting to its application in geology. Although, earthquake seismology preceded exploration applications [1]; Mallet [2], 1845 experimented with “artificial earthquakes” in an attempt to measure seismic velocities. Knott [3], 1899 developed the theory of reflection and refraction at interfaces while Zoeppritz and Wiechert published on wave theory in 1907 [1].

The developed refraction theory forms the basis for this study which is therefore concerned with the development of computer software for the interpretation of seismic refraction data and computation of engineering parameters. This research was born out of the necessity to ease the problem of cumbersome manual interpretation and computation of seismic data. It focuses on the development of a computer program for use in seismic refraction interpretation as related to engineering studies.

2. THEORETICAL DEVELOPMENT

The foundation of seismic refraction theory is Snell’s law, which governs the refraction of sound or light rays across the boundary between layers of different physical properties. As waves travel from a medium of low seismic velocity into a medium of higher seismic velocity, some are refracted toward the lower velocity medium in the higher velocity medium and some are reflected back into the first medium. As the angle of incidence of the wave approaches the critical angle (an angle where the refracted ray grazes the surface of the interface between the two media or refracted angle = 90\(^0\)), most of the compressional energy is transmitted along the interface with significant acoustic impedance contrast with the velocity of the second layer.

As this energy propagates along the interface, it generate new waves in the upper medium that in turn propagate back to the surface at the critical angle with the seismic velocity of the first layer. For seismic refraction to work, therefore, the velocity of seismic waves in the lower layer must be greater than the velocity of the wave in the above layer. When this condition is met,
the refracted wave arrives at the Earth’s surface where it can be detected by geophones which generates an electrical signal and send the signal to a seismograph.

From a series of geophones placed on the ground surface, the seismic arrival time versus the shot-to-detonator distances can be plotted to give a Time–Distance (T-X) curve. Figs. 1 and 2 show the geometry of refracted ray paths for planar and dipping two layer case, while Figs. 3 and 4 show the typical travel-time (T-X) graph for a two layer case and faulted bed respectively.

The theoretical equations used in writing the program are listed below:

For planar layer,

\[
T_n = \frac{x}{v_1} + \sum_{i=1}^{n-1} \frac{2z_i\sqrt{v_1^2 - v_2^2}}{v_{i-1}v_i} \quad \text{... (1)}
\]

For dipping two layer case (Fig. 2),

\[
T_d = \frac{2\mu \cos i_c}{v_1} + \frac{x \sin (i_c + \alpha)}{v_2} \quad \text{... (2)}
\]

\[
T_n = \frac{2\mu \cos i_c}{v_1} + \frac{x \sin (i_c - \alpha)}{v_2} \quad \text{... (3)}
\]

\[
i_c = \frac{1}{2} \left( \sin^{-1} \frac{v_1}{v_{2d}} + \sin^{-1} \frac{v_1}{v_{2d}} \right) \quad \text{... (4)}
\]

\[
\text{Where,} \quad X = \text{Offset} \\
\text{Z = Depth to the Refractor} \\
i_c = \text{Critical angle} \\
S = \text{Shot point} \\
G_1 \text{ and } G_2 = \text{Geophones}
\]

**Fig. 1. Geometry of a Planar Interface Refracted Ray Paths (2-Layers)**
Where, $Z_d = \text{Perpendicular Depth down-dip}$
$D_d = \text{Vertical Depth Down-dip}$
$Z_u = \text{Perpendicular Depth up-dip}$
$D_u = \text{Vertical Depth Up-dip}$
$\alpha = \text{Angle of dip of the refractor (interface)}.$

Fig. 2. Seismic Refraction Geometry of a Dipping Interface (2-Layers)

Where,
$T_i = \text{Intercept time}$
$X_c = \text{Cross-over distance}$

Fig. 3. Typical Travel-Time (T-X) Curve for a Two Layer Case
Fig. 4. Typical T-X graph for a Faulted Bed (Vertical Displacement)

\[ \alpha = \frac{1}{2} \left\{ \sin^{-1} \frac{V_1}{V_{2d}} - \sin^{-1} \frac{V_1}{V_{2u}} \right\} \]  

Where, \( T_n \) is the total travel-time to the nth layer (in ms or s)
\( V_n \) is the velocity of the nth layer in m/s
\( Z_n \) is the thickness of the nth layer in meters (m)
\( X \) is the offset in meters (m)
\( \alpha \) is the critical angle of the incident seismic wave energy in degrees.
\( \alpha \) is the dip of the refractor
\( V_{2d} \) is the velocity of the second layer down-dip
\( V_{2u} \) is the velocity of the second layer up-dip

The following equations were used to determine the velocity and thicknesses of the subsurface layers from the T-X graph; For planar interface,

\[ V_1 = \frac{1}{S_1} \]  

\[ V_2 = \frac{1}{S_2} \]  

Where \( S_1 \) is the slope of the direct wave and
\( S_2 \) is the slope of the refracted wave.

To determine the velocity of the second layer for a dipping interface, it is necessary to carry out a reverse shooting (Fig. 2). The velocity \( V_2 \) of the second layer could be evaluated using equation 8 [4],
Thicknesses were determined using the equations below; For Intercept-Time Method,

$$Z = \frac{T_i V_1 V_2}{2 \sqrt{(V_2^2 - V_1^2)}}$$ .............................. (9)

For Cross-Over Distance Method,

$$Z = \frac{x_c}{2} \sqrt{\frac{V_2 - V_1}{V_1 + V_2}}^{1/2}$$ .............................. (10)

where, $V_1$ and $V_2$ are the determined velocities of first and second layer respectively
$T_i$ is the intercept time where the refracted segment crosses the time axis
$x_c$ is the distance when the arrival time for direct wave is equal to that of the refracted wave and $Z$ is the layer thickness.

Depth ($D_n$) could be estimated by summing up the thickness values i.e.

$$D_n = Z_1 + Z_2 + Z_3 + \ldots + Z_{n-1}$$ .............................. (11)

The throw of a fault ($\Delta Z$) could also be determined by relating the equation of the first intercept time ($T_{i_1}$) of the second layer and the second intercept time ($T_{i_2}$) of the second layer (Fig. 4);

$$\Delta Z = \frac{\Delta T_1 V_1 V_2}{2 \sqrt{(V_2^2 - V_1^2)}}$$ .............................. (12)

The equations for the two types of thickness that could be determined in a dipping interface are as follows:

For Perpendicular Thickness,

$$Z_u = \frac{T_u V_1}{2 \cos \theta_c}$$ .............................. (13)

$$Z_d = \frac{T_d V_2}{2 \cos \theta_c}$$ .............................. (14)

For Vertical Thickness,

$$D_u = \frac{Z_u}{\cos \theta_c}$$ .............................. (15)

$$D_d = \frac{Z_d}{\cos \theta_c}$$ .............................. (16)

Where, $D_u$ and $D_d$ are the vertical thicknesses up-dip and down-dip respectively and $Z_u$ and $Z_d$ are the vertical thicknesses up-dip and down-dip respectively
The equations used for the computation of engineering parameters include:

\[ V_p = \left( \frac{k + \frac{1}{2} \mu}{\rho} \right)^{1/2} \]  \hspace{1cm} (17)

\[ V_s = \left( \frac{\mu}{\rho} \right)^{1/2} \]  \hspace{1cm} (18)

Where \( V_p \) = compressional wave velocity; \( V_s \) = shear wave velocity; \( \mu \) = shear modulus/rigidity modulus; \( K \) = bulk modulus; and \( \rho \) = density.

The bulk modulus,

\[ K = \frac{E}{3-2\sigma} \]  \hspace{1cm} (19)

and rigidity modulus, \( \mu = \frac{E}{2+2\sigma} \)  \hspace{1cm} (20)

Where \( E \) is the Young Modulus, \( \sigma \) is the Poisson’s Ratio \((0 < \sigma < \frac{1}{2})\), [4,5].

The velocity ratio ‘\( R \)’ can be written as;

\[ R = \frac{V_p}{V_s} = \frac{2-2\sigma}{\sqrt{1-2\sigma}} \]  \hspace{1cm} (21)

\[ \sigma = \frac{\rho^2 - 2}{2\rho^2 - \gamma} \]  \hspace{1cm} (22)

and

\[ E = \frac{\rho K}{(1-\sigma)(1+\sigma)} \]  \hspace{1cm} (23)

Porosity (\( \phi \)) was estimated from the equation,

\[ \phi = \frac{V_p(V_m - V_f)}{V_b(V_m - V_f)} \]  \hspace{1cm} (24)

Where \( V_b \) is the Bulk Velocity of the formation, \( V_f \) is the P-wave velocity in the fluid saturating the rock formation, \( V_m \) is the velocity of the rock matrix, and \( \Phi \) is Porosity.

Laboratory constants such as Fracture Frequency (\( n \)) and Rock Quality Designation (RQD) were evaluated from the equations below [6];

\[ n = \frac{1}{k_2} \cdot \frac{(V_b - V_f)}{V_s V_p} \]  \hspace{1cm} (25)

\[ RQD = \frac{1}{k_2} \cdot \frac{(V_b - V_f)}{V_s V_p} \] \hspace{1cm} (26)
Where \( n \) = number of cracks (fracture)/m
\( \text{RQD} \) = Rock Quality Designation
\( K_2 \) = constant
\( V_0 \) = velocity of fractured rock
\( V_1 \) = velocity of solid (unfractured) rock
\( V_p \) = Field observed Compressional Wave Velocity

3. METHODOLOGY

The adopted methodology is as shown in Fig. 5. The interpretation technique adopted by the developed software is a quantitative method of interpretation which provides information on the strength and bearing capacity of earth materials. It involves Forward Modeling Technique by comparing field interpretation model with theoretically generated interpretation model.

Seismic data (secondary) were obtained for use in the testing of the efficiency of the software. The data were analyzed and interpreted using the developed software, to model the nature of the subsurface bedrock.

3.1 Design of Windows-Based Seismic Refraction Interpretation Software

The seismic refraction interpretation software was designed using Visual Basic Programming Language Tools. The tools include the Form, Command Button, Label Control, Textbox control, Control Dialogue Control, etc (Fig. 6).

3.2 Design Procedure

The software was designed following procedures such as: Welcome Interface, Field Data Input, Interpretation, Result, View/Print and Storage (Fig. 7).

3.2.1 Welcome interface

The Welcome interface was first designed using VB tools such as label and command button control tools. This interface was designed for the user to be able to select at start-up whether to continue or to quit (Fig. 8).

3.2.2 Field data input

The software worksheets were designed for seismic data input. Various Seismic refraction field and laboratory data such as Single On Shot, On and Reverse Shot, Fracture Frequency and Rock Quality Designation data can be input in the program worksheet (Fig. 9).
Fig. 5. Workflow Chart showing the methodology used for the study
Fig. 6. Common visual basic tools, features and controls

Fig. 7. Flow chart of designed data interpretation software
Fig. 8. The software (seissoft) application welcome interface

Fig. 9. Typical field data entry form
3.2.3 **Interpretation**

This stage of design involves the incorporation of the slope parameters and intercepts into the computer program to generate layer parameters such as Velocity, Thickness and Depth. There are interpretation GUIs (Graphic User Interface) designed for Planar Interface (Single On Shot and On and Reverse Shot), Dipping Interface (On and Reverse Shot), Faulted Bed, Fracture Frequency and Rock Quality Designation (Fig. 10).

3.2.4 **Result**

The result of every process or calculation would be displayed visibly on the User Interface in the text box designed for it (Fig. 10).

3.2.5 **View/print**

A section of the software was also designed to view seismic refraction plots. These plots can be displayed on the Main Menu Screen (Fig. 11). The viewed graph can be printed by the user, by clicking on the Print submenu from the Main Menu to print a hard copy of the plot displayed on the screen.

3.2.6 **Storage**

The software was designed for the input seismic refraction field data to be stored on the computer hard disk and removable secondary medium as a backup copy with the aid of the Save Menu. The data is saved in the .DAT format or notepad or All Files.

![Layer Parameters (Single On Shot)](image_url)

**Fig. 10. Typical data interpretation form**
4. THE COMPUTER PROGRAM

The computer software algorithm was developed using the equations 1-26. The developed algorithms were fed into the Microsoft Visual Basic interpreter, debugged and run.

5. APPLICATION OF THE SOFTWARE

Available data such as Single On Shot, On and Reverse Shot and Engineering Elastic Constant data were obtained and interpreted using the software developed. Laboratory data were not available. The data were initially interpreted manually and later interpreted using the developed software.

One of the Single On Shot plot interpreted using the software is shown in Fig. 12. The interpreted layer parameters are shown in Fig. 13. The interpreted parameters were derived by obtaining the slope parameters from the plot interface. The slope parameters were obtained by moving the cursor over the line to a satisfied position for selecting slope. The point values are shown on the right-hand side top corner of the interface (Fig. 12).

The obtained slope parameters serve as input into the Xa, Xb, ta and tb textboxes of the interpretation interface (Fig. 13). The appropriate command and option buttons were selected to obtain the Velocities, Thickness and Depth.
Fig. 12. Typical single shot time-distance (T-X) plot displayed by the seissoft software

Fig. 13. A Typical single on shot interpretation interface showing the derived layer parameters
Fig. 14 is a multi-layer Single On shot plot and the interpreted parameter interface is shown in Fig. 15. Fig. 16 is a Faulted bed Single On shot plot and the interpreted parameter interface is shown in Fig. 17. The throw of the fault was calculated to be 20.10 m. A typical On and Reverse shot plot is shown in Fig. 18. The interpreted layer parameters are shown on the interface in Fig. 19. The interpretation revealed that it is also the case of a dipping layer interface. Therefore, it was interpreted for the dipping layer parameters with the refractor having a dip angle of about 4.5° and the critical angle of the shot to the refractor interface is about 30°. The true velocity of the second layer was estimated as 3071 m/s while the Vertical Depth to the refractor beneath Forward shot point and Reverse shot point was interpreted to be 41.02 m and 22.96 m respectively (Figs. 20 and 21).

Engineering elastic constant data was obtained and interpreted, it was interpreted to have a Velocity ratio of 1.667, Poisson ratio of 0.21875, Young Modulus of 110.565 and Bulk Modulus of 65.52 (Fig. 22). The Bulk modulus (K) is used to estimate the strength of the bedrock which is estimated to be of High Strength since the value is greater than 60 GPa. The estimated Porosity value as shown in Fig. 23 is 0.0625. The value is far less than 1 showing that the bedrock is less porous; therefore the bedrock is of high strength and good for any engineering construction.
Fig. 15. Single shot 4 layer parameters interpretation

Fig. 16. Faulted bed single on shot time-distance (T-X) plot
Fig. 17. Faulted bed single on shot layer parameters interpretation

Fig. 18. Forward and reverse shot data time-distance (T-X) Plot
Fig. 19. Forward and reverse shot interpretation layer parameters

Fig. 20. Dipping interface (forward shot point) model layer parameters
Fig. 21. Dipping interface (reverse shot point) model layer parameters

Fig. 22. Elastic Constant Interface showing the Interpreted Data and its Results
A comparison of the manual interpretation and software interpreted results was done for Single Shot 1. The comparison shows great similarity in the results with a percentage velocity variation of 0% and percentage thickness variation of 0.1%. The comparison of the results of the manually computed and SeisSoft interpreted data is shown in Table 1. The summary of the results of the computed and interpreted data are shown in Table 2. Nevertheless, the limitation of the software application is that it could not pick layer slope parameters automatically.

### Table 1. Comparison of results of single shot 1 seismic refraction data

<table>
<thead>
<tr>
<th>Layer number</th>
<th>Manual results</th>
<th>Seissoft application results</th>
<th>% Variation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Velocity (m/s)</td>
<td>Thickness (m)</td>
<td>Velocity (m/s)</td>
</tr>
<tr>
<td>1</td>
<td>2000</td>
<td>8.95</td>
<td>2000</td>
</tr>
<tr>
<td>2</td>
<td>4000</td>
<td>-</td>
<td>4000</td>
</tr>
</tbody>
</table>
Table 2. Summary of Interpretation Results of Seismic Refraction Data

<table>
<thead>
<tr>
<th>Data Name</th>
<th>No. of Layers</th>
<th>Layer Parameters</th>
<th>General Lithological Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Velocity (m/s)</td>
<td>Depth (m)</td>
</tr>
<tr>
<td>Single Shot 1</td>
<td>1</td>
<td>2000</td>
<td>8.95</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>4000</td>
<td>-</td>
</tr>
<tr>
<td>Single Shot 4</td>
<td>1</td>
<td>2500</td>
<td>11.4</td>
</tr>
<tr>
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<td>2</td>
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</tr>
<tr>
<td></td>
<td>4</td>
<td>20,000</td>
<td>-</td>
</tr>
<tr>
<td>Faulted Single</td>
<td>1</td>
<td>5456</td>
<td>30.06-50.16</td>
</tr>
<tr>
<td>Shot</td>
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<td>16,952</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>18,000</td>
<td>20.10</td>
</tr>
<tr>
<td>On and Reverse</td>
<td>1</td>
<td>1500</td>
<td>15.68-28.03</td>
</tr>
<tr>
<td>Shot</td>
<td>2</td>
<td>3071</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>4.5º</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Critical Angle</td>
</tr>
</tbody>
</table>

6. CONCLUSION

Computer software for seismic refraction data interpretation and determination of engineering parameters has been developed for different data types. The software was developed using Microsoft Visual Basic Programming Language. It could display its result within a fraction of a minute.

The software having performed efficient in that its interpretation results are the same or almost the same with that of manual calculations would aid the speed and accuracy of results in engineering geophysics.

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COMPETING INTERESTS

Authors declare that there are no competing interests.

REFERENCES


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