



Development of Computer Software for Seismic Refraction Data Interpretation and Engineering Parameters Determination

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Authors' contributions

This work was carried out in collaboration between all authors. Author OEB designed the study, wrote the algorithm, developed the software, and wrote the first draft of the manuscript. Authors OEB and OJA managed the analyses of the study and literature searches. All authors read and approved the final manuscript.

Original Research Article

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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 interprete 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°), 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-detector 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,

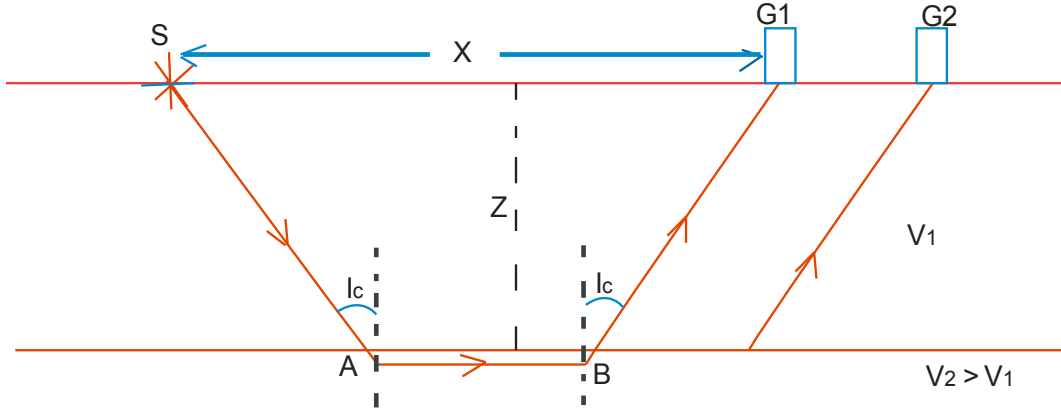
$$T_n = \frac{X}{v_n} + \sum_{n=1}^{n-1} \frac{2Z_n \sqrt{(v_n^2 - v_{n-1}^2)}}{v_{n-1} v_n} \dots\dots\dots (1)$$

For dipping two layer case (Fig. 2),

$$\therefore T_d = \frac{2Zd \cos i_c}{v_1} + \frac{X \sin (i_c + \alpha)}{v_1} \dots\dots\dots (2)$$

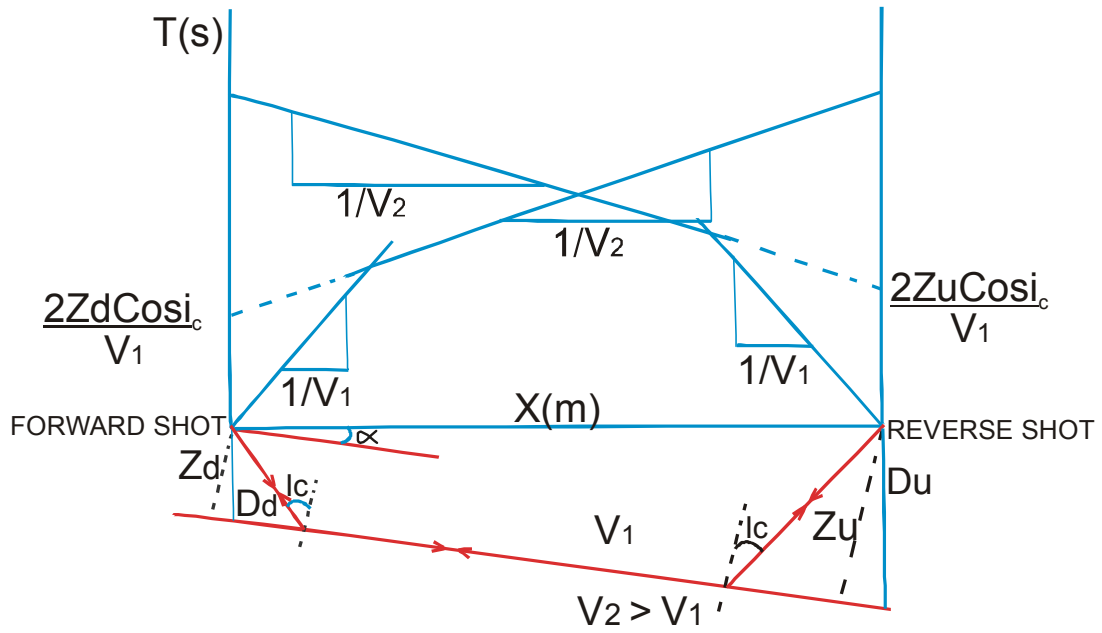
$$T_u = \frac{2Zu \cos i_c}{v_1} + \frac{X \sin (i_c - \alpha)}{v_1} \dots\dots\dots (3)$$

$$i_c = 1/2 \left\{ \sin^{-1} \frac{v_1}{v_{2d}} + \sin^{-1} \frac{v_1}{v_{2u}} \right\} \dots\dots\dots (4)$$



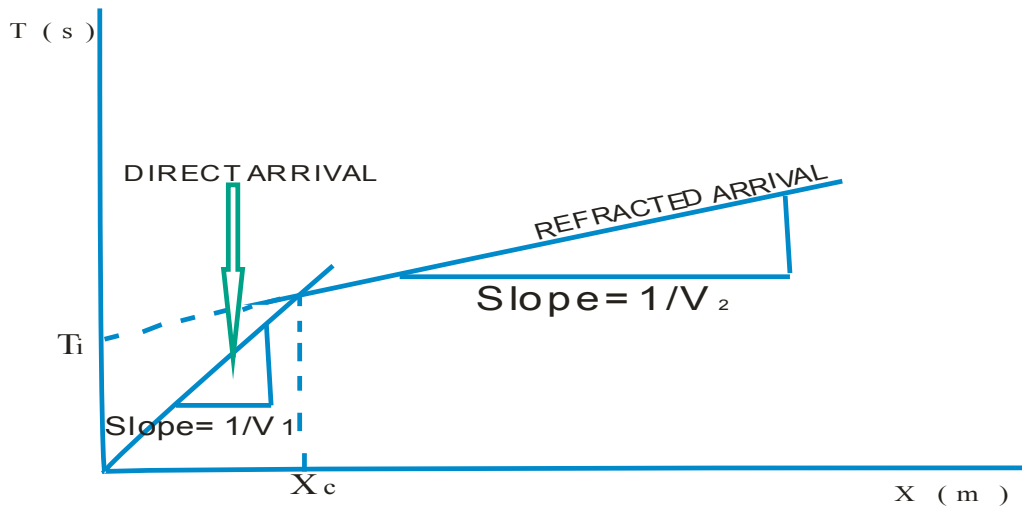
Where,
 X = Offset
 Z = Depth to the Refractor
 i_c = Critical angle
 S = Shot point
 G₁ and G₂ = Geophones

Fig. 1. Geometry of a Planar Interface Refracted Ray Paths (2-Layers)



Where, Z_d = Perpendicular Depth down-dip
 Z_u = Perpendicular Depth up-dip
 α = Angle of dip of the refractor (interface).
 D_d = Vertical Depth Down-dip
 D_u = Vertical Depth Up-dip

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



Where,
 T_i = Intercept time
 X_c = Cross-over distance

Fig. 3. Typical Travel-Time (T-X) Curve for a Two Layer Case

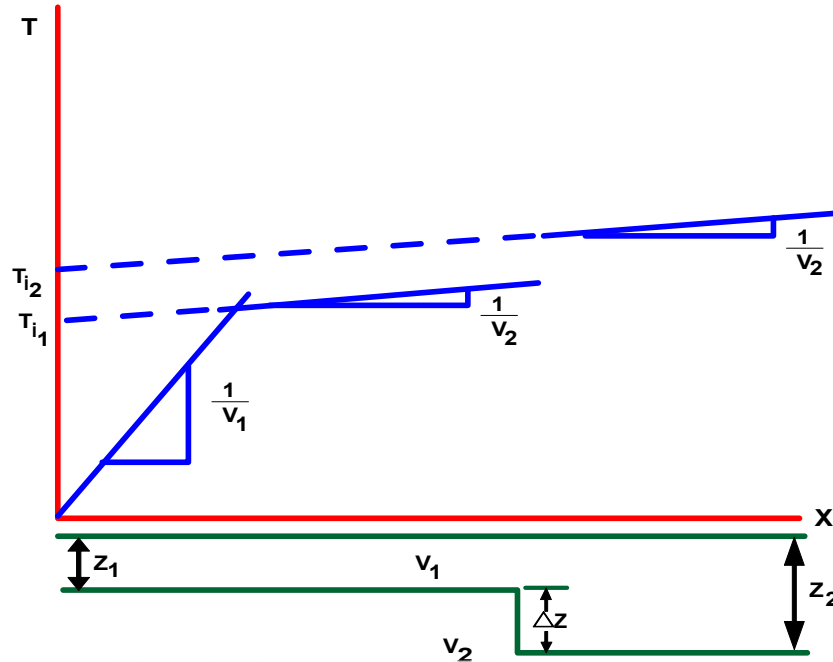


Fig. 4. Typical T-X graph for a Faulted Bed (Vertical Displacement)

$$\alpha = 1/2 \left\{ \sin^{-1} \frac{v_1}{v_{2d}} - \sin^{-1} \frac{v_1}{v_{2u}} \right\} \dots\dots\dots (5)$$

- 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)
- i_c is the critical angle of the incident seismic wave energy in degrees.
- α 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,

$$V_1 = \frac{1}{S_1} \dots\dots\dots (6)$$

$$V_2 = \frac{1}{S_2} \dots\dots\dots (7)$$

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],

$$V_2 = 2 \left(\frac{V_d V_u}{V_d + V_u} \right) \dots\dots\dots (8)$$

Thicknesses were determined using the equations below; For Intercept-Time Method,

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

For Cross-Over Distance Method,

$$Z = \frac{X_c}{2} \left[\frac{V_2 - V_1}{V_2 + V_1} \right]^{1/2} \dots\dots\dots (10)$$

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.

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

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

The throw of a fault (ΔZ) 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);

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

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

For Perpendicular Thickness,

$$Z_u = \frac{T_u V_1}{2 \cos i_c} \dots\dots\dots (13)$$

$$Z_d = \frac{T_d V_1}{2 \cos i_c} \dots\dots\dots (14)$$

For Vertical Thickness,

$$D_u = \frac{Z_u}{\cos i_c} \dots\dots\dots (15)$$

$$D_d = \frac{Z_d}{\cos i_c} \dots\dots\dots (16)$$

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:

$$V_p = \left(\frac{K + 4/3\mu}{\rho} \right)^{1/2} \dots\dots\dots (17)$$

$$V_s = \left(\frac{\mu}{\rho} \right)^{1/2} \dots\dots\dots (18)$$

Where V_p = compressional wave velocity;
 V_s = shear wave velocity;
 μ = shear modulus/rigidity modulus;
 K = bulk modulus; and
 ρ = density.

The bulk modulus,

$$K = \frac{E}{3-6\sigma} \dots\dots\dots (19)$$

and rigidity modulus, $\mu = \frac{E}{2+2\sigma} \dots\dots\dots (20)$

Where E is the Young Modulus, σ is the Poisson's Ratio ($0 < \sigma < 1/2$), [4,5].

The velocity ratio 'R' can be written as;

$$R = \frac{V_p}{V_s} = \sqrt{\frac{2-2\sigma}{1-2\sigma}} \dots\dots\dots (21)$$

$$\sigma = \frac{R^2 - 2}{2R^2 - 2} \dots\dots\dots (22)$$

and

$$E = \frac{\rho V_p^2 (1-2\sigma)(1+\sigma)}{(1-\sigma)} \dots\dots\dots (23)$$

Porosity (ϕ) was estimated from the equation,

$$\phi = \frac{V_f(V_m - V_b)}{V_b(V_m - V_f)} \dots\dots\dots (24)$$

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
 ϕ is Porosity.

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

$$n = \frac{1}{K_2} \cdot \frac{(V_1 - V_p)}{V_1 V_p} \dots\dots\dots (25)$$

$$RQD = \frac{1}{K_2} \cdot \frac{(V_0 - V_p)}{V_0 V_p} \dots\dots\dots (26)$$

Where n = number of cracks (fracture)/m
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).

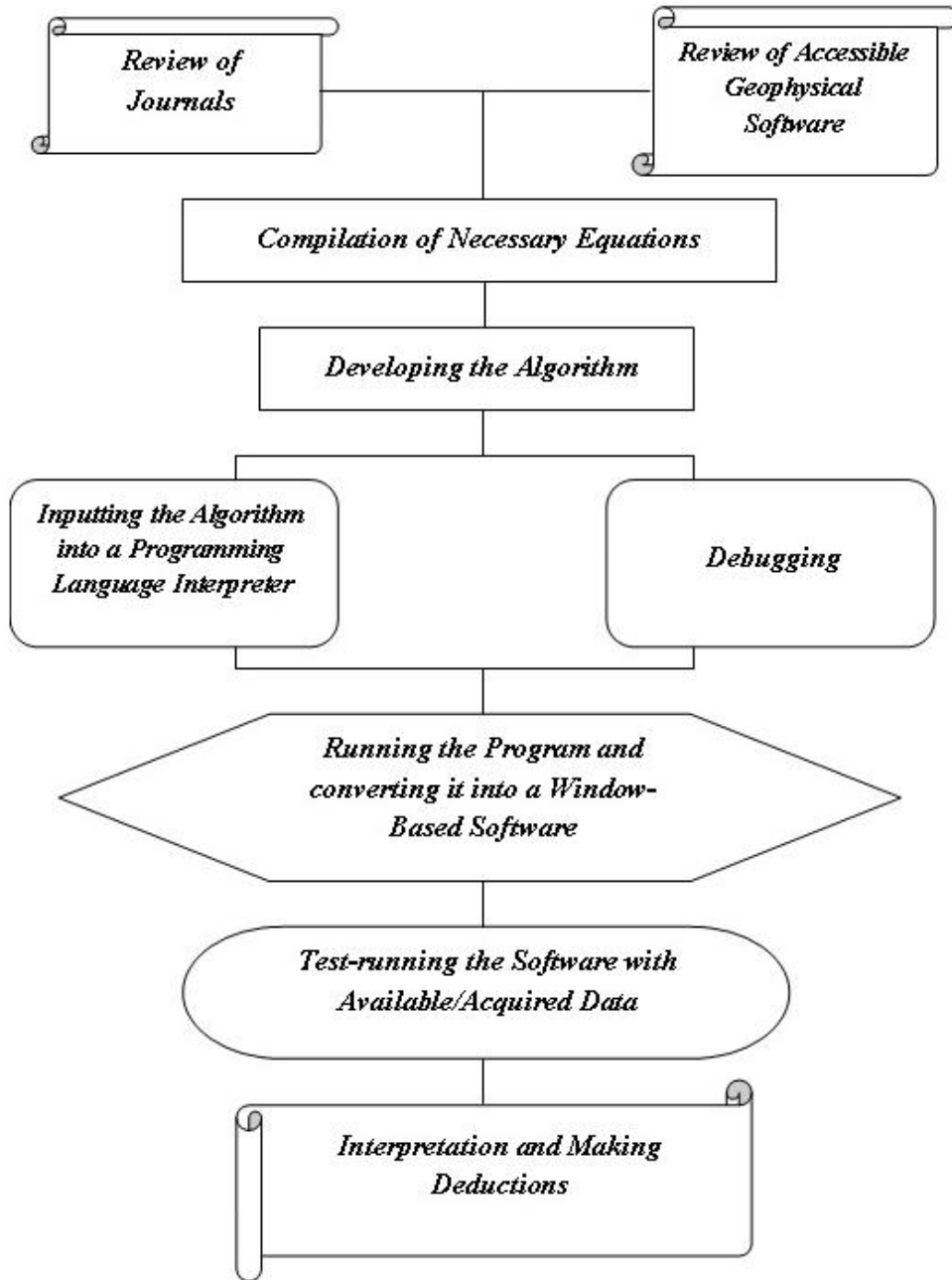


Fig. 5. Workflow Chart showing the methodology used for the study

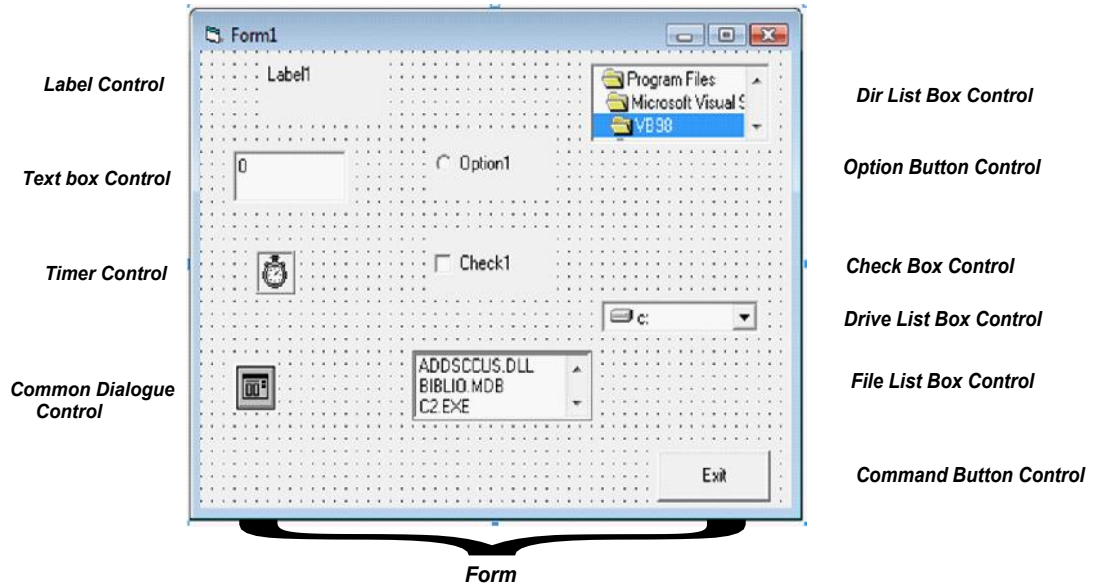


Fig. 6. Common visual basic tools, features and controls

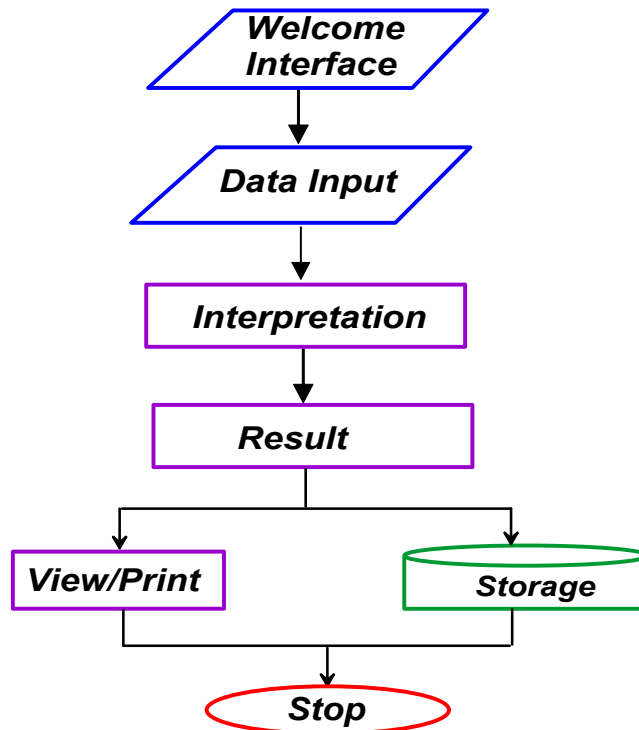


Fig. 7. Flow chart of designed data interpretation software



Fig. 8. The software (seissoft) application welcome interface

Serial No	Offset(m)	Time(ms)	Serial No	Offset(m)	Time(ms)	Serial No	Offset(m)	Time(ms)
1	0	0	21	0	0	41	0	0
2	0	0	22	0	0	42	0	0
3	0	0	23	0	0	43	0	0
4	0	0	24	0	0	44	0	0
5	0	0	25	0	0	45	0	0
6	0	0	26	0	0	46	0	0
7	0	0	27	0	0	47	0	0
8	0	0	28	0	0	48	0	0
9	0	0	29	0	0	49	0	0
10	0	0	30	0	0	50	0	0
11	0	0	31	0	0	51	0	0
12	0	0	32	0	0	52	0	0
13	0	0	33	0	0	53	0	0
14	0	0	34	0	0	54	0	0
15	0	0	35	0	0	55	0	0
16	0	0	36	0	0	56	0	0
17	0	0	37	0	0	57	0	0
18	0	0	38	0	0	58	0	0
19	0	0	39	0	0	59	0	0
20	0	0	40	0	0	60	0	0

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.

Layers	Xa(m)	Xb(m)	ta(s)	tb(s)	Vel.(m/s)	Thickness(m)	Depth(m)
1	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0

Thicknesses

- 1st Layer
- 2nd Layer
- 3rd Layer
- 4th Layer
- 5th Layer
- 6th Layer
- 7th Layer
- 8th Layer
- 9th Layer

Depths

- 1st Refractor
- 2nd Refractor
- 3rd Refractor
- 4th Refractor
- 5th Refractor
- 6th Refractor
- 7th Refractor
- 8th Refractor
- 9th Refractor

Buttons: Calculate Layer Velocities, Save, Print, Exit, CALCULATE LAYER THICKNESS, Calculate Layer Depths

Fig. 10. Typical data interpretation form

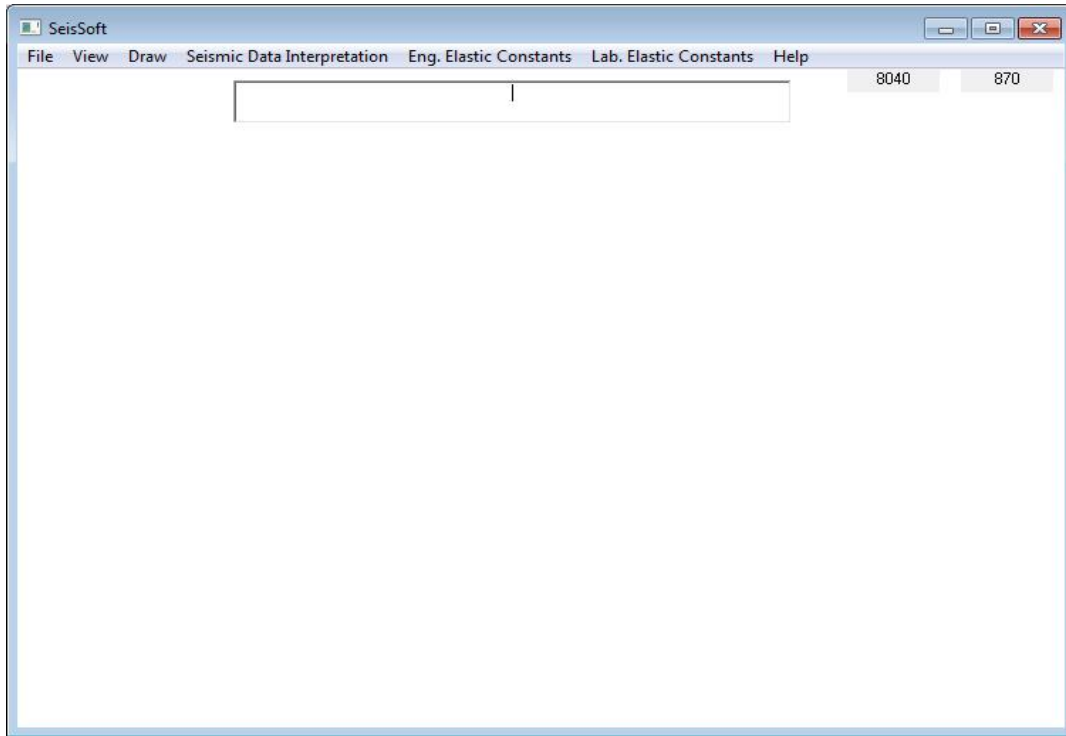


Fig. 11. Main Menu Form

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 X_a , X_b , t_a and t_b textboxes of the interpretation interface (Fig. 13). The appropriate command and option buttons were selected to obtain the Velocities, Thickness and Depth.

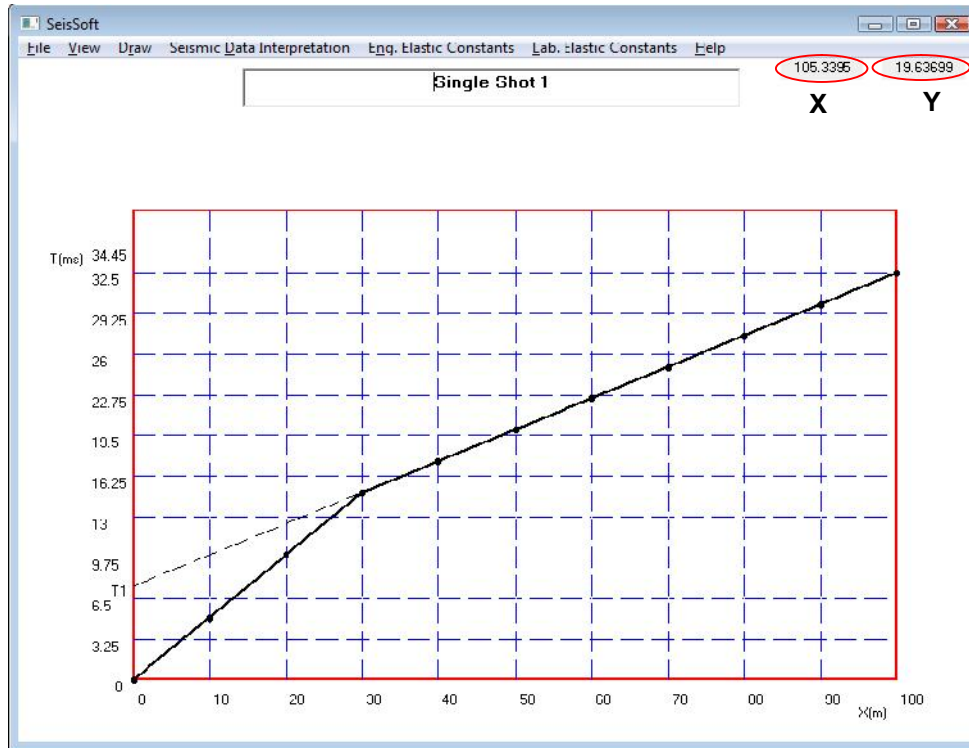


Fig. 12. Typical single shot time-distance (T-X) plot displayed by the seisssoft software

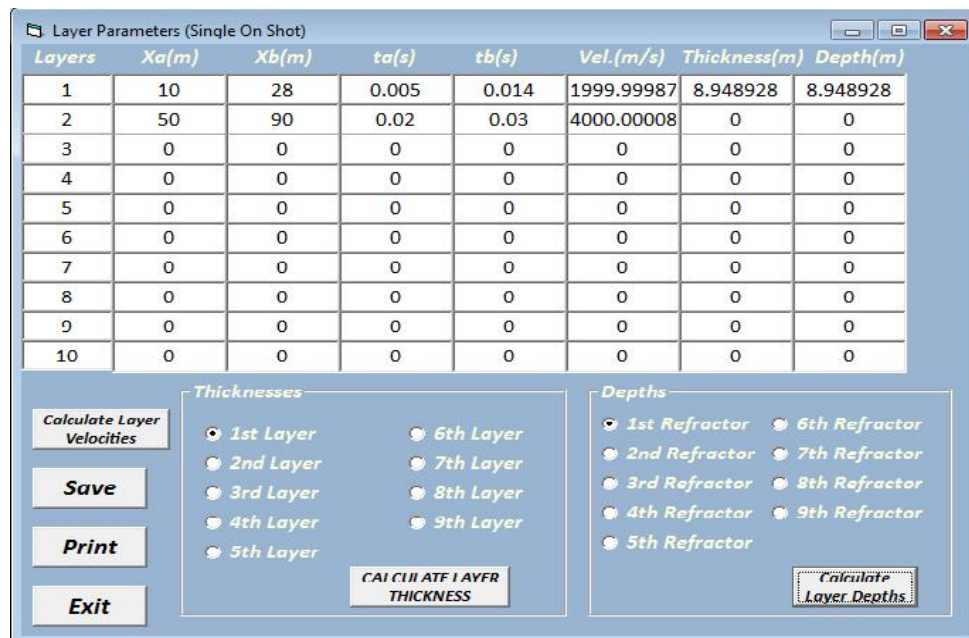


Fig. 13. A Typical single on shot interpretation interface showing the derived layer parameters

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.

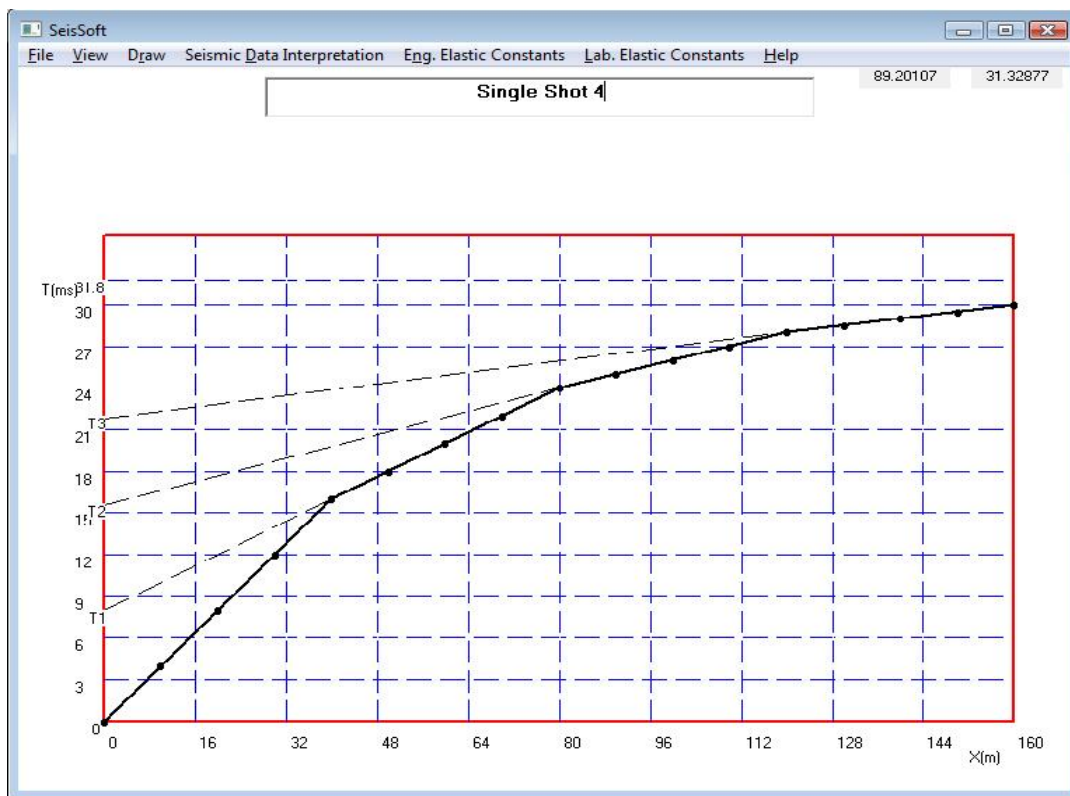


Fig. 14. Single shot 4 time-distance (T-X) plot

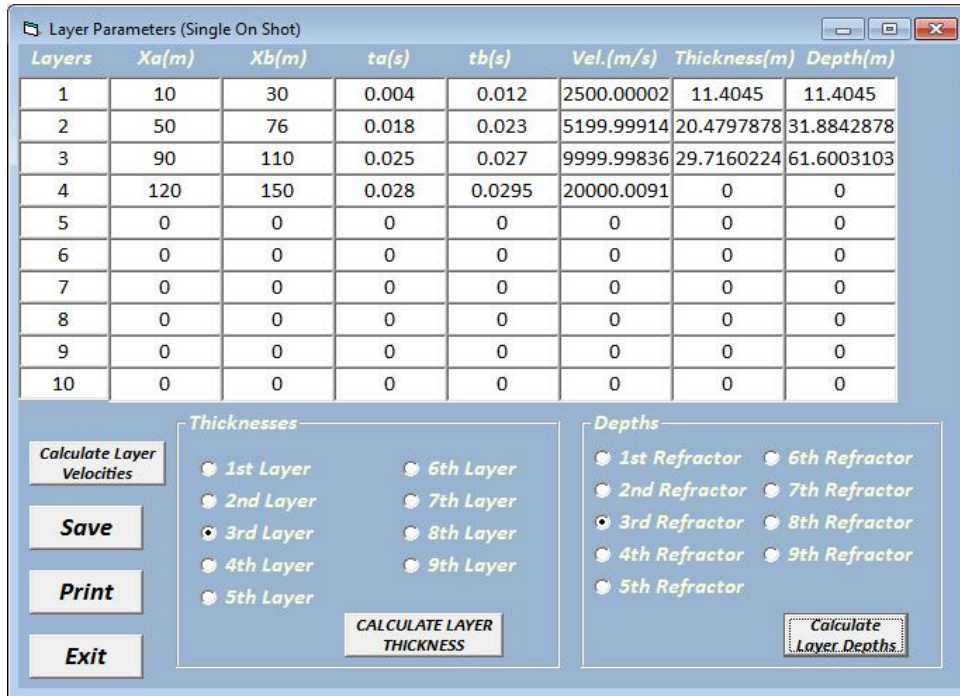


Fig. 15. Single shot 4 layer parameters interpretation

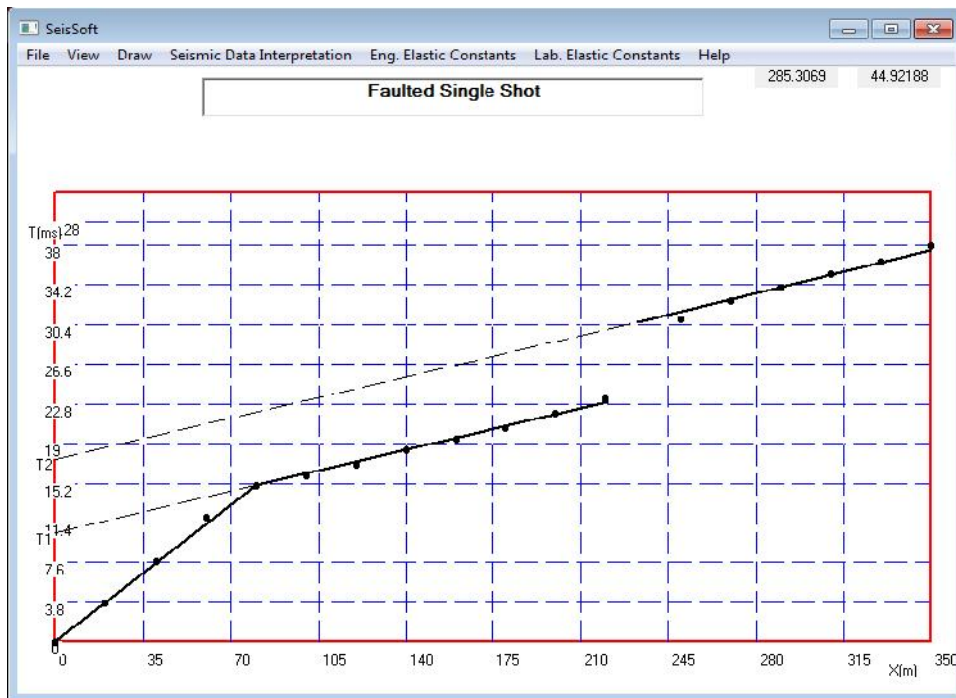


Fig. 16. Faulted bed single on shot time-distance (T-X) plot

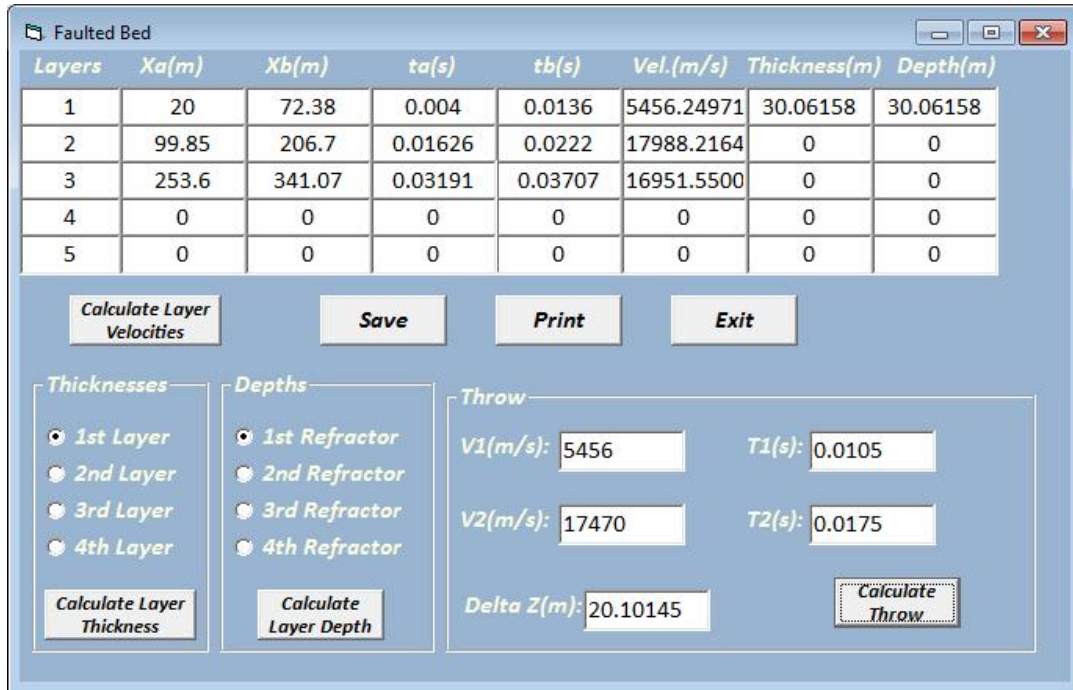


Fig. 17. Faulted bed single on shot layer parameters interpretation

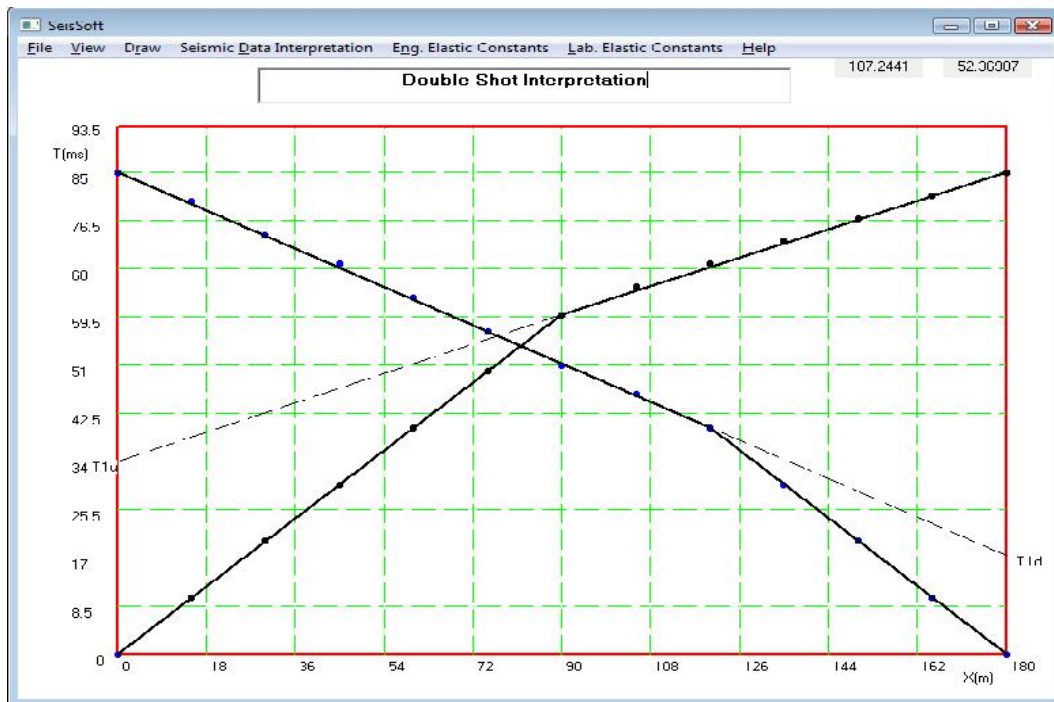


Fig. 18. Forward and reverse shot data time-distance (T-X) Plot

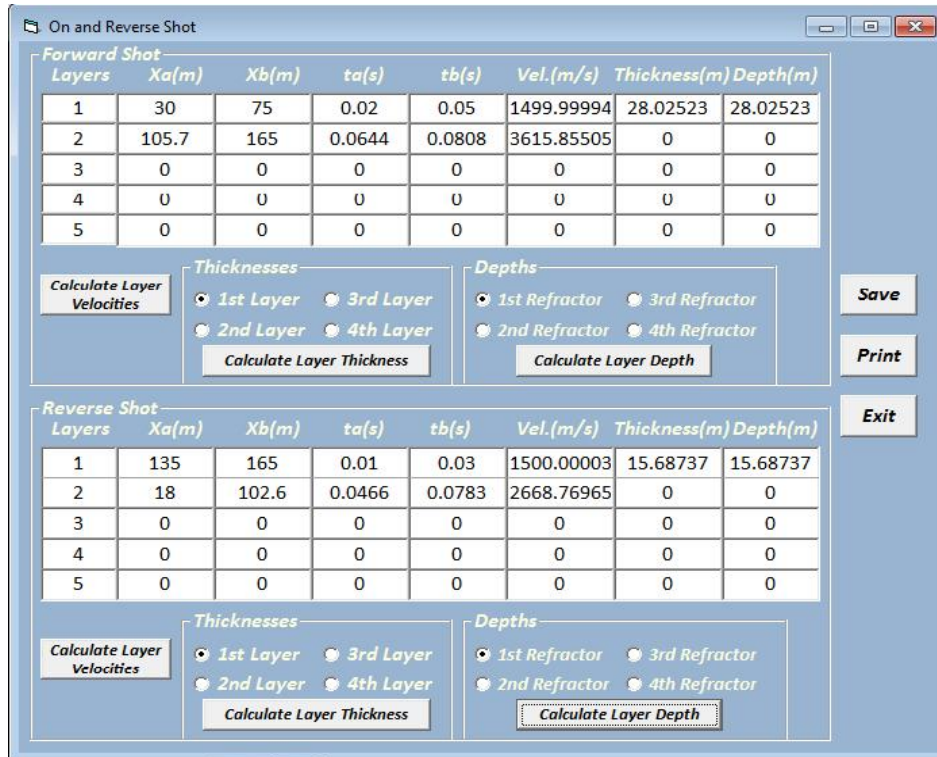


Fig. 19. Forward and reverse shot interpretation layer parameters

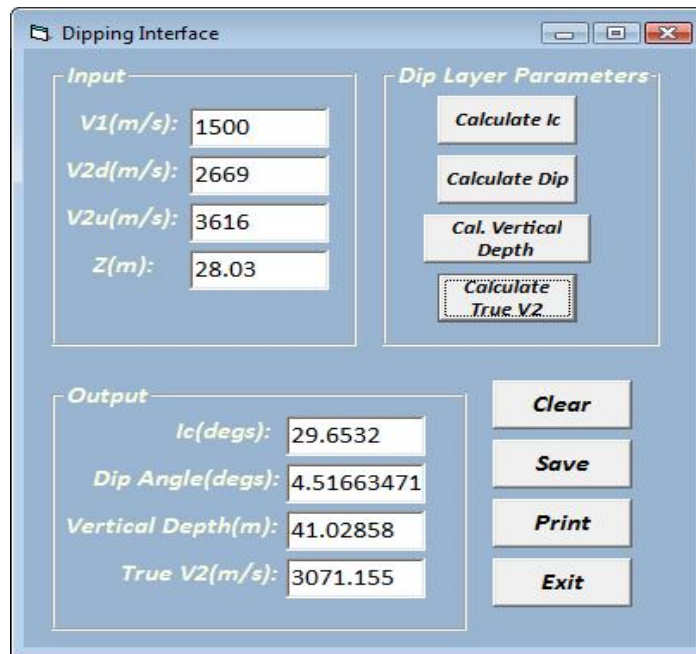


Fig. 20. Dipping interface (forward shot point) model layer parameters

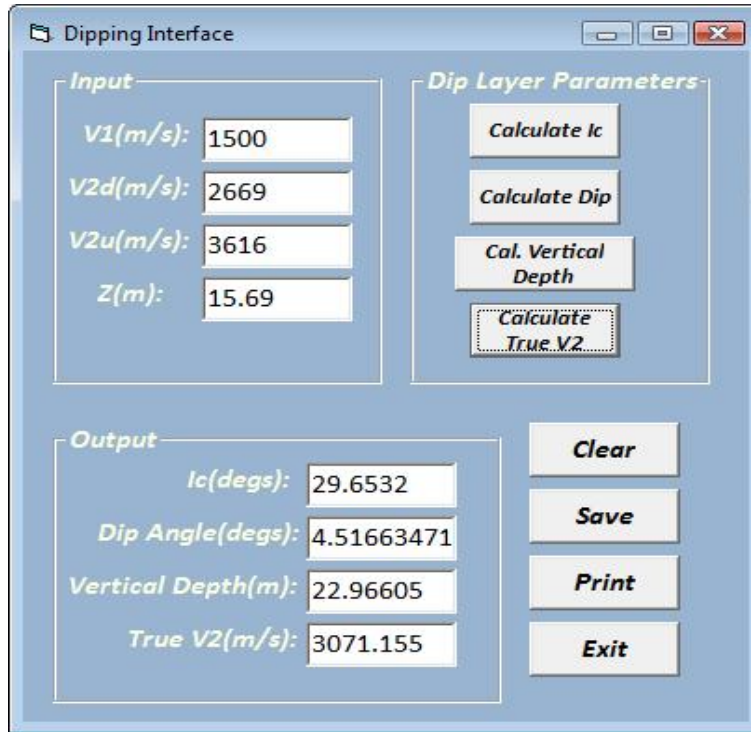


Fig. 21. Dipping interface (reverse shot point) model layer parameters

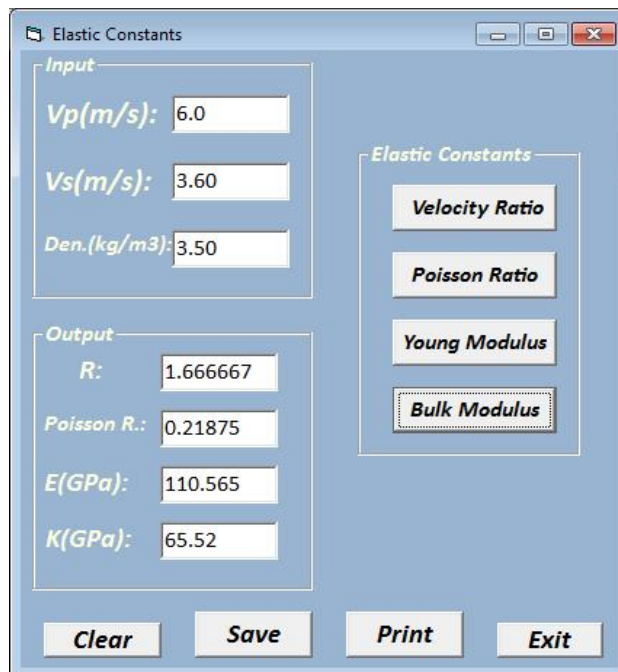


Fig. 22. Elastic Constant Interface showing the Interpreted Data and its Results

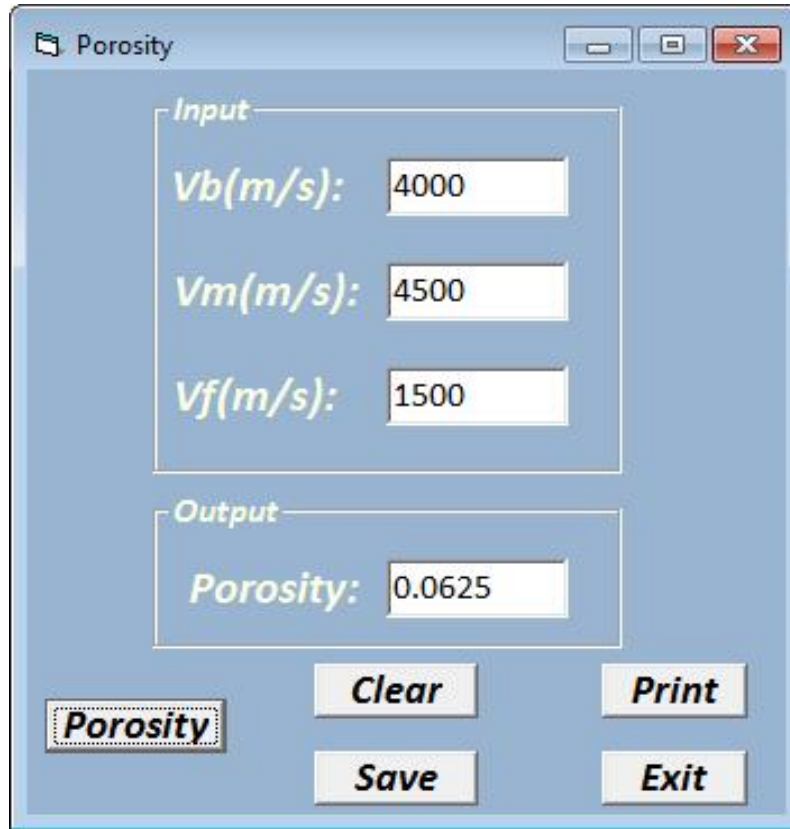


Fig. 23. Porosity interface showing the interpreted data and its result

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

Layer number	Manual results		Seissoft application results		% Variation	
	Velocity (m/s)	Thickness (m)	Velocity (m/s)	Thickness (m)	Velocity	Thickness
1	2000	8.95	2000	8.9489	0%	0.1%
2	4000	-	4000	-	0%	-

Table 2. Summary of Interpretation Results of Seismic Refraction Data

Data Name	No. of Layers	Layer Parameters		General Lithological Characteristics
		Velocity (m/s)	Depth (m)	
Single Shot 1	1	2000	8.95	Partly Loose Sandstone
	2	4000	-	Consolidated Sandstone
Single Shot 4	1	2500	11.4	Sandstone/Shale
	2	5200	31.89	Limestone/Dolomite
	3	10,000	61.60	Highly consolidated Sandstone
	4	20,000	-	Basement Rock
Faulted Single Shot	1	5456	30.06-50.16	Limestone/Dolomite
	2	16,952 - 18,000	-	Consolidated Sandstone/ Basement Rock
		Fault Throw	20.10	
On and	1	1500	15.68-28.03	Wet Sand
Reverse Shot	2	3071	-	Consolidated Sandstone/ Shale/Limestone
		Dip Angle	4.5°	
		Critical Angle	30°	

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.

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