Implementation of Hagedoorn's Plus-Minus method in Matlab GUI

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ABSTRACT

The basic theory of seismic refraction and one of the most popular refraction methods—plus-minus are elaborated. Despite of the limitations of plus-minus method, such as can only deal with single interface model with inclination angle smaller than $10°$ and efficient only in "analyze window", researchers benefit by its convenience to roughly explore the subsurface structure and acquire significant information of layers. This pragmatic method is realized in Matlab as a graphical user interface (GUI), as a more approachable tool for beginners. From finite difference model and field data tests, usability of the tool is proved.

INTRODUCTION

Among all methods of seismology, refraction exploration serves as a significant part and possesses its own advantages. Refraction generates when seismic wave meets interface of a stratum and its underlying medium which has relatively higher velocity, it travels along interface under a critical incident angle and excites new up-going wave that can be detected by geophones on surface. This provides geophysicists with abundant underground information.

Comparing to reflection, the more expansive coverage of refracted wave allows us to collect information from wider region. Also, we are able to extract attributes of two adjacent media from a single refraction travel time against moveout relationship due to characters of its trajectory. Regarding refracted wave, many research have been done aiming at seismic tomography. Here lists some main methods appeared during its evolvement:

(1) Migrated forward and reverse delay times (Gardner, 1939). This method calls for a datum to calibrate all the arrival times. Get the refractor velocity from it then delay times at source and receivers through series of calculation. Transform time into depth in the end;
(2) Plus-minus method (Hagedoorn, 1959). Hagedoorn gave out a geometrical method based on the crossing refraction profile. According to his theory, "minus" time provides refractor velocity while "plus" time includes information of refractor depth;
(3) Generalized reciprocal method (GRM) (Palmer, 1981) can be used to manage highly irregular interfaces. There is an ideal distance "XY" that makes up-going components form different path have almost the same emergent point. Which simplifies the velocity analysis and makes the most coherent time-depth profile. GRM is the general situation of plusminus method.

This paper will focus on Hagedoorn's plus-minus method, reexplore it in Matlab* to let more people experience its convenient.

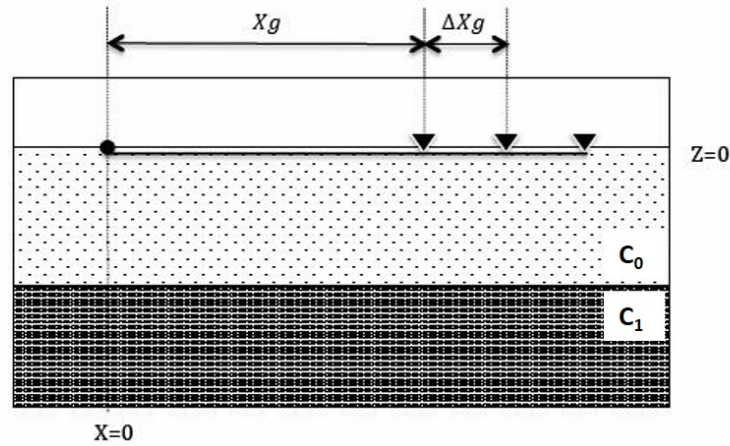*A mathematical software developed by Mathworks,Inc.

FIG. 1. Direct arrival in horizontal single interface model

THEORY FOUNDATIONS

Refraction methods

Direct arrival

Direct arrival refers to the wave that goes directly from source to receiver along surface (when source and receivers are all on surface). According to this attribute, we are able to determine the medium velocity through its travel-time against offset formula.

Empirically give out the formula

$$\tau_D(X_g) = \frac{X_g}{C_0}, \tag{1}$$

Refracted arrival

According to Fermat's principle, the ray (i.e. seismic wave in this case) incident at angle θ_i will change direction when meeting the boundary of two apparently velocity-different media. It departs from the interface upwards at angle θ_t as is shown in figure 2.

In Snell's Law, there is

$$\frac{\sin \theta_i}{C_0} = \frac{\sin \theta_t}{C_1}. \tag{2}$$

Which leads to

$$\sin \theta_t = \sin \theta_i \frac{C_1}{C_0}. \tag{3}$$

If $C_1 > C_0$, which means that the lower medium has higher velocity than its covering stratum, $\sin \theta_t$ will always be greater than $\sin \theta_i$. Because *sine* is monotone increasing in the range of incident and transmitted angles ($0° \sim 90°$), we can say that $\theta_t > \theta_i$.
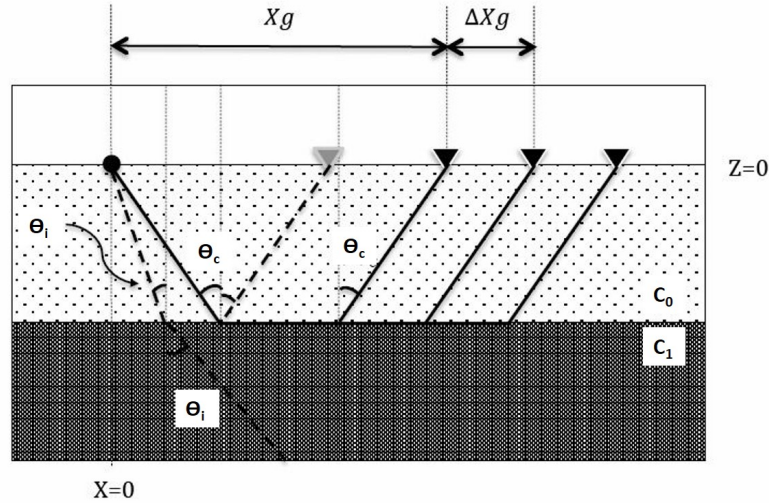
FIG. 2. Refracted arrival in horizontal single interface model

In similar velocity models as figure 2, the transmitted ray is always more horizontal than incident ray. While θ_t cannot increase infinitely as θ_i getting greater, there must be a point when seismic wave incomes in a certain angle, $\theta_t = 90°$.

It is when

$$\sin 90° = 1 = \sin \theta_i \frac{C_1}{C_0}, \tag{4}$$

$$\theta_i = \theta_c = \sin^{-1}(\frac{C_0}{C_1}). \tag{5}$$

This special angle θ_i is called critical angle θ_c when transmitted wave propagates along layers' interface rather than in lower medium.

Since the upper and lower media are tightly contacting, propagation of the critical transmission will cause vibration in the upper medium again. The vibration excites a new wave, which goes upwards to geophones on surface, is called *refraction arrival*.

In shot gathers, refracted arrival presents to be a straight line crossing direct arrival at a certain point. From which we can assume the relationship of refraction travel-time and offset to be linear in the following form,

$$\tau_R(X_g) = m_R X_g + \tau_{R0}. \tag{6}$$

First focus on the slope m_R. In figure 3, the spacing between geophone A and B is ΔX_g, assume that the refracted arrival takes time τ to travel from source to geophone A and $\Delta\tau$ more time to B than A, then these equations must be correct,

$$\tau = m_R X_g + \tau_{R0}, \tag{7}$$

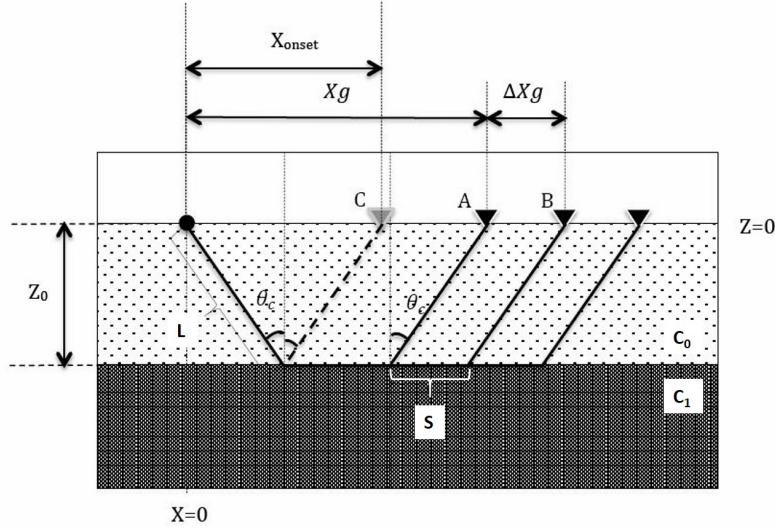$$\tau + \Delta\tau = m_R(X_g + \Delta X_g) + \tau_{R0}. \tag{8}$$

FIG. 3. Refraction to different geophones

Subtract equation 8 by 7, we get

$$\Delta\tau = m_R \Delta X_g. \tag{9}$$

Easy to know that ΔX_g is equal to S, so the only difference between ray paths to geophone A and B is S by lower medium velocity C_1, then there is

$$m_R = \frac{\Delta\tau}{\Delta X_g} = \frac{1}{\frac{\Delta X_g}{\Delta\tau}} = \frac{1}{C_1}. \tag{10}$$

The slope of refraction travel time is only related to C_1.

The intercept τ_{R0} cannot be zero because even if source and geophone are in the same position, it still takes time for the refracted wave to travel back and forth in the upper layer. Since only τ_{R0} is undetermined now, one known point on the ray path will solve it.

A special case among refracted arrivals is caught by geophone C. It is special because it is the critical point where refracted wave starts to appear. Name the offset of geophone C X_{onset}.

Analyze the relationships among Z_0, L and X_{onset}, there are

$$L = \frac{Z_0}{\cos\theta_c}, \frac{X_{onset}}{2} = Z_0 \tan\theta_c \tag{11}$$

According to equation 6,

$$\frac{2L}{C_0} = \frac{X_{onset}}{C_1} + \tau_{R0} \tag{12}$$

Substitute equation 11 into 12,

$$\frac{2Z_0}{C_0 \cos\theta_c} = \frac{2Z_0 \tan\theta_c}{C_1} + \tau_{R0} \tag{13}$$

Futher,

$$\tau_{R0} = \frac{2Z_0 C_1 - 2Z_0 C_0 \sin \theta_c}{C_0 C_1 \cos \theta_c} \tag{14}$$

Use equation 5, and 14 becomes

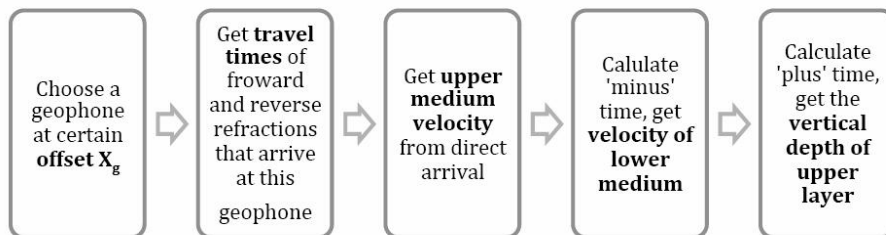$$\tau_{R0} = \frac{2Z_0 \cos \theta_c}{C_0}. \tag{15}$$

Reviewing the original linear formula, the relationship between refraction travel time and offset finally improves into,

$$\tau_R(X_g) = \frac{X_g}{C_1} + \frac{2Z_0 \cos \theta_c}{C_0}. \tag{16}$$

Plus-minus method

The *plus-minus method* is a geophysical principle raised by J.G.Hagedoorn (1959), it appeared as an improvement to Thronburgh's wave-front theory (Thornburgh, 1930) in regions that subsurface velocity distribution is unascertained. Plus-minus interprets seismic refraction profiles from symmetrical shot points over irregular strata whose inclined angles are less than $10°$. Generally, the "plus" part of it helps determine the vertical thickness of the layer upon refractor at different offsets and the "minus" part contains the information of lower layer velocity (figure 4).

Here is a flow chart showing the procedure of using plus-minus method:

Choose a geophone at certain **offset X_g**	Get **travel times** of froward and reverse refractions that arrive at this geophone	Get **upper medium velocity** from direct arrival	Calulate 'minus' time, get **velocity of lower medium**	Calculate 'plus' time, get the **vertical depth of upper layer**

An important thing is, this plus-minus method is only effective in an "analyze window", which is the region covered by reciprocal directions' refractions (see figure 5).

Delay times

The plus-minus method considers the refraction travel-time formula in delay-time theory.
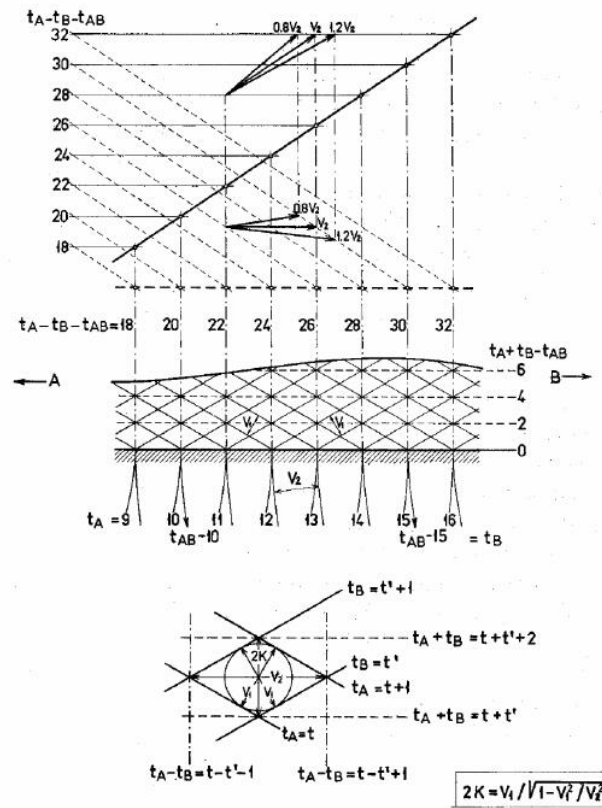
FIG. 4. A very simple example demonstrating the principles of the "Plus-Minus" method (Hage-doorn, 1959)
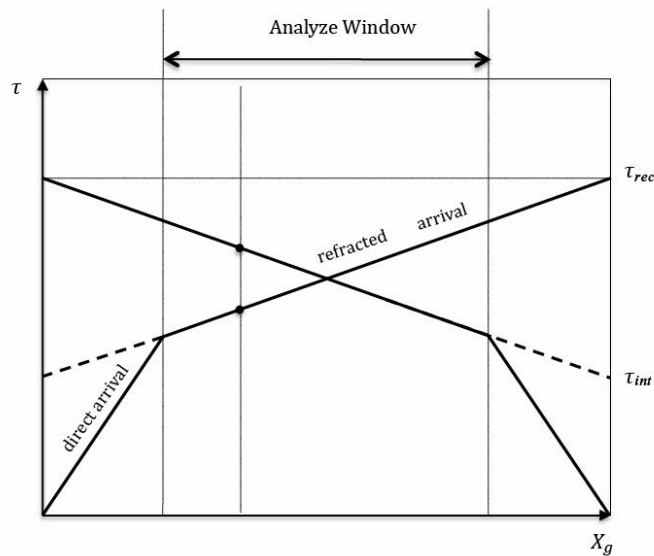

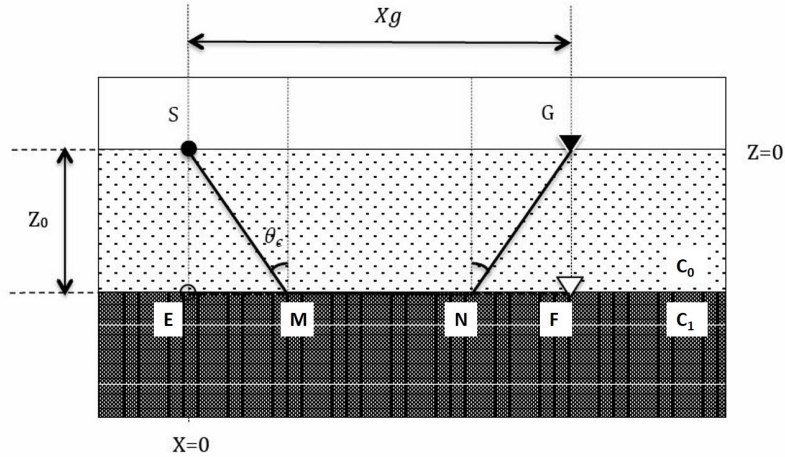FIG. 5. The "analyze window" for plus-minus method

FIG. 6. The "delay time" in refracted wave propagation

In the single interface model, in equation

$$\tau_R(X_g) = \frac{X_g}{C_1} + \tau_{R0} \tag{17}$$

the first part on right can be regarded as the time the wave-front travels from source S's perpendicular sub point E on refractor to geophone G's perpendicular sub point F by velocity C_1 (see figure 6).

To reflect the real travel time of refraction, $\frac{X_g}{C_1}$ has to be fixed by the delayed time that refraction travels along SM instead of EM as well as along NG instead of NF.

Respectively, we name delay time related to source δ_s and delay time related to geophone δ_g, then equation 17 become,

$$\tau_R(X_g) = \frac{X_g}{C_1} + \delta_s + \delta_g. \tag{18}$$

Because
$$\delta_s = \frac{SM}{C_0} - \frac{EM}{C_1} = \frac{Z_0}{C_0 \cos\theta_c} - \frac{Z_0 \tan\theta_c}{C_1} = \frac{Z_0 \cos\theta_c}{C_0} \tag{19}$$

and $\delta_g = \dfrac{Z_0 \cos\theta_c}{C_0}$ for the same reason, the travel-time formula obtained in this way coincides exactly with equation 16.

Hagedoorn's plus-minus method

As was mentioned above, the plus-minus method is for extrapolating irregular interface whose slope changes along horizon are not so strenuous. In figure 7, series of geophones are set over the objective interface, receiving the forward and reverse refracted arrivals from the reciprocal sources on both ends.
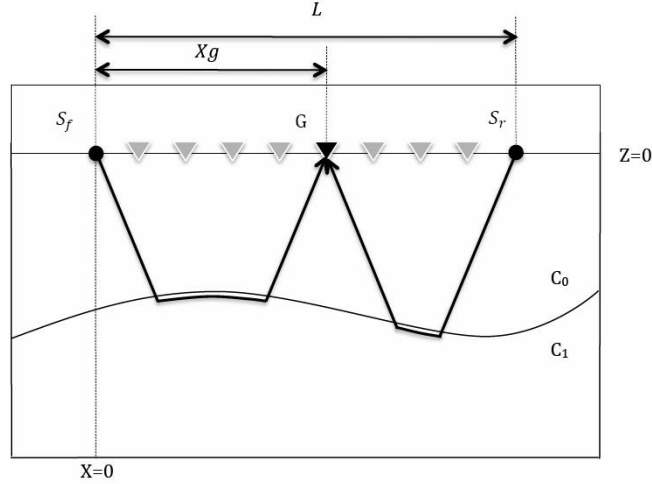
FIG. 7. One pair of forward and reverse shots over irregular interface

Investigating one of the geophones and its corresponding pair of forward and reverse shots. Their travel time expressions in delay time format are

$$\tau_{Rf}(X_g) = \frac{X_g}{C_1} + \delta_{sf} + \delta_g. \tag{20}$$

$$\tau_{Rr}(X_g) = \frac{L - X_g}{C_1} + \delta_{sr} + \delta_g. \tag{21}$$

Define Hagedoorn's "minus" time as

$$\begin{aligned}
\tau^-(X_g) &= \tau_{Rf} - \tau_{Rr} - \tau_{rec} \\
&= \frac{2X_g - L}{C_1} + \delta_{sf} - \delta_{sr} - \tau_{rec} = \frac{2X_g}{C_1} + \left(\delta_{sf} - \delta_{sr} - \frac{L}{C_1} - \tau_{rec}\right)
\end{aligned} \tag{22}$$

τ_{rec} represents the time that a wave front travels from forward source to reverse source (or in the opposite way).

No need to solve the equation, because C_1 is only related to the slope of the $\tau^-(X_g)$ curve, if the slope is m^-, then

$$C_1 = \frac{2}{m^-}. \tag{23}$$

Similarly, define "plus" time as

$$\tau^+(X_g) = \tau_{Rf} + \tau_{Rr} - \tau_{rec} \tag{24}$$

from equation 20, 21, we know that

$$\begin{aligned}
\tau^+(X_g) &= \frac{L}{C_1} + \delta_{sf} + \delta_{sr} + 2\delta_g - \tau_{rec} \\
&= \tau_{rec} + 2\delta_g - \tau_{rec} = 2\delta_g
\end{aligned} \tag{25}$$

So

$$\tau^+(X_g) = 2\delta_g = \frac{2Z_0 \cos \theta_c}{C_0}. \tag{26}$$

Upper medium velocity C_0 can be solved from direct arrival. Combining with C_1 from equation 23, the critical angle θ_c can be derived. With these information, the vertical depth at certain X_g can be calculated as follow

$$Z_0 = \frac{C_0}{2 \cos \theta_c} \tau^+(X_g). \tag{27}$$

In practice, plus-minus method helps to simulate the shape of objective interface by combining vertical depth at each offset within analyze window. Indeed, this method is just approximative, but there is "no justification for using very precise methods when the interpretation is quite uncertain anyway owning to the undetectable ambiguities"(Gardner, 1939).

Source and geophones in different burying depth

In field works, source and geophones are not always on the same horizon, the discrepancy of their burying depth can extend or shorten the length of ray path, which influences the accuracy of plus-minus result. To eliminate error, reanalyze the components of refraction ray.

According to figure 8, name the delay times in thickness d_g δ_1 and δ_2 corresponding to S_f and S_r, δ_{sf} and δ_{sr} now indicate the delay times in thickness Z' instead. Refraction travel time from forward shot is

$$\tau_{Rf}(X_g) = \frac{X_g}{C_1} + \delta_{sf} + \delta_1 + \delta_g \tag{28}$$

and for reverse shot is

$$\tau_{Rr}(X_g) = \frac{L - X_g}{C_1} + \delta_{sr} + \delta_2 + \delta_g. \tag{29}$$

Then

$$\tau^- = \frac{2X_g}{C_1} + (\delta_{sf} - \delta_{sr} + \delta_1 - \delta_2 - \tau_{rec}) \tag{30}$$

No doubt, the lower layer velocity C_1 is still the same as in equation 23. But new elements in ray path affect plus time,

$$\tau^+ = \frac{L}{C_1} + (\delta_{sf} + \delta_{sr} + \delta_1 + \delta_2 + 2\delta_g - \tau_{rec}) = 2\delta_g + \frac{\delta_1 + \delta_2}{2}. \tag{31}$$
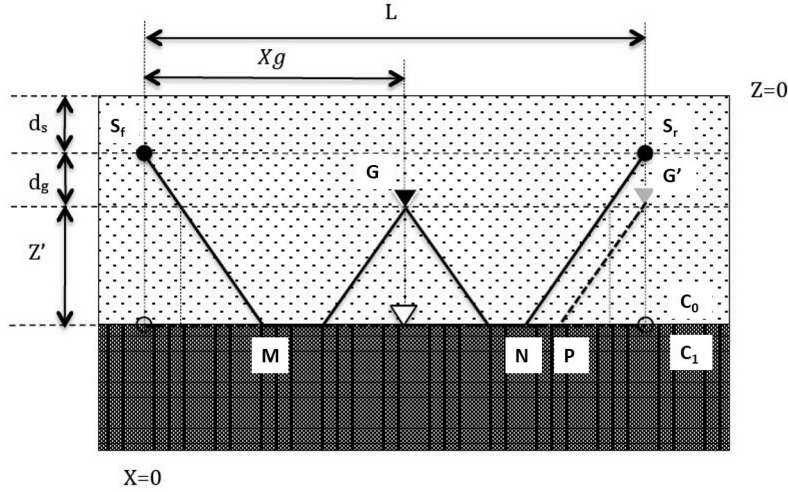
FIG. 8. Refraction in situation that source and geophones are in different depths

Inspect the two opposite directions, the forward reciprocal time means the wave travels along S_f-M-P-G'. Due to different burial depth of source and receivers, the upward traveling segment of refraction ray omits thickness d_g. Thus, write forward reciprocal time as

$$\tau_{rec1} = \frac{L}{C_1} + \delta_{sf} + \delta_{sr} + \delta_1 \tag{32}$$

Reverse reciprocal time will be

$$\tau_{rec2} = \frac{L}{C_1} + \delta_{sf} + \delta_{sr} + \delta_2 \tag{33}$$

Get τ_{rec} from their mean value,

$$\tau_{rec} = \frac{\tau_{rec1} + \tau_{rec2}}{2} = \frac{L}{C_1} + \delta_{sf} + \delta_{sr} + \frac{\delta_1 + \delta_2}{2} \tag{34}$$

this makes equation 31.

Now look into plus time in detail,

$$\delta_g = \frac{Z' \cos \theta_c}{C_0} \tag{35}$$

$$\delta_1 = \delta_2 = \frac{d_g}{C_0 \cos \theta_c} - \frac{d_g}{C_1 \tan \theta_c} = \frac{d_g \cos \theta_c}{C_0} \tag{36}$$

So

$$\tau^+ = \frac{2(z' + \frac{d_g}{2}) \cos \theta_c}{C_0} \tag{37}$$

$$Z' + \frac{d_g}{2} = \frac{C_0 \tau^+}{2 \cos \theta_c}. \tag{38}$$

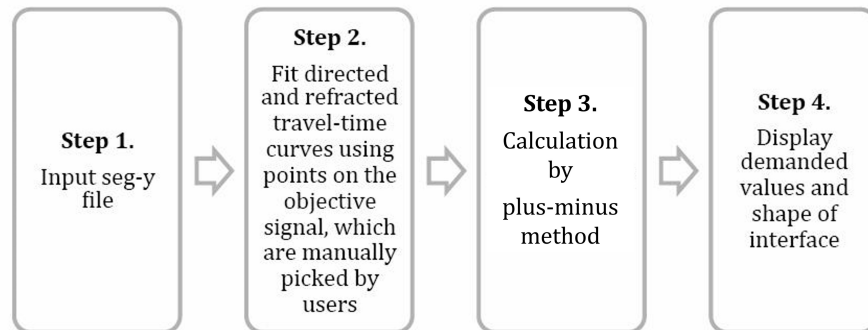To get the real perpendicular thickness Z of upper layer,

$$Z = Z' + d_g + d_s = \frac{C_0 \tau^+}{2 \cos \theta_c} + \frac{d_g}{2} + d_s. \tag{39}$$

THE GRAPHICAL USER INTERFACE (GUI) OF PLUS-MINUS METHOD

Design idea

In this research, the plus-minus method is realized as a graphical user interface (GUI) in Matlab named "pm" with the help of CREWES' toolbox (Youzwishen et al., 1999). The main function of the user interface is to acquire information of the subsurface refractor and its covering strata and display them in visual forms.

"pm" works as follow:

Step 1.
Input seg-y file

Step 2.
Fit directed and refracted travel-time curves using points on the objective signal, which are manually picked by users

Step 3.
Calculation by plus-minus method

Step 4.
Display demanded values and shape of interface

Program

The program is composed of three functional parts according to the working procedure: importing record, picking signal and processing data.

Importing Record

"pm"reads seismic record in seg-y format—one of the most popular formats of seismic data worldwide. In some records, in-line data is complied together. By choosing range of trace, it can display the specified part of record that users want to deal with.

Picking signal and saving data

Direct and refraction signals are easy to be identified in record, so we collect their information by manually picking points. Fit curves based on the picked points to recover the signal, then resample on it to get uniformly distribute data points to smoothen the final simulated interface.

Code:

Picking points:

```matlab
disp(['User selected ', fullfile(pathname, filename)])
cd(pathname);
[dataout, sampint, textheader] = altreadsegy(filename,'textheader','yes');
disp(textheader);
p=get(findobj('tag','checkbox1'),'Value');
if isequal(p,1)
    trace1=str2double(get(findobj('tag','edit1'),'string'));
    trace2=str2double(get(findobj('tag','edit2'),'string'));
    shot_1=dataout(:,trace1:trace2);
    [m,n] = size(shot_1);
    x=0:gs:n*gs;
    t = 0:sampint:(m-1)*sampint;
    imagesc(x,t,shot_1,[-1*gain,gain]);
    xlabel('Lateral position x (m)');
    ylabel('Time (sec)');

else
    [m,n] = size(dataout);
    x=0:gs:n*gs;
    t = 0:sampint:(m-1)*sampint;
    imagesc(x,t,dataout,[-1*gain,gain]);
    xlabel('Lateral position x (m)');
    ylabel('Time (sec)');
end
```

Saving data:

```matlab
%make line by clicking points on the signal
clickaline;
disp('press MB3 and then any key to finish picking curve');
pause
```

Save data:

```matlab
% resample
handles.rst_data=sortrows(handles.idata,1);
xdata=handles.rst_data(:,1);
ydata=handles.rst_data(:,2);
n=4;
np=80;
p=polyfit(xdata,ydata,n);
trec1=polyval(p,sr);
trec2=str2double(get(findobj('tag','edit12'),'string'));
if trec2>0
    trec=(trec1+trec2)/2;
    set(findobj('tag','edit12'),'string',num2str(trec));
else
    set(findobj('tag','edit12'),'string',num2str(trec1));
end
xnew=[sf:(sr-sf)/(np-1):sr];
ynew=polyval(p,xnew);
handles.nidata=[];
handles.nidata(:,1)=xnew;
handles.nidata(:,2)=ynew;


%save
index=find(handles.nidata(:,1)>=xf & handles.nidata(:,1)<=xr);
fdata=handles.nidata(index,:);
dlmwrite('F signal.txt',fdata);
```

Processing data

With the data of objective signal, we are able to deduce all useful values by plus-minus method. Specially, "pm" gets refractor velocity C_1 from the inverse slope of refraction rather than τ^-, which is supported by equation 20, 21. The two methods have almost the same precision, however counting from τ^- calls the program for one more curve fitting (τ^-), thus will potentially increase the error of the result.

Plotting the depth along offset allow us to see the rebuilt interface. C_0, C_1 and τ_{rec} are also displayed in corresponding frames.

Code:

C_0(v1 in program):

```
V = load('Direct Wave.txt');
xd1= min(V(:,1));
xd2= max(V(:,1));
td1= min(V(:,2));
td2= max(V(:,2));
v1=(xd2-xd1)/(td2-td1);
```

C_1(v2 in program):

```
%get V2
n=1;
p=polyfit(M(:,1),M(:,2),n);
v2a=1/p(1);
p=polyfit(N(:,1),N(:,2),n);
v2b=-1/p(1);
v2=(v2a+v2b)/2;
sin=v1/v2;
cos= abs(sqrt(1-sin*sin));
```

τ_{rec}:

```
% resample
handles.rst_data=sortrows(handles.idata,1);
xdata=handles.rst_data(:,1);
ydata=handles.rst_data(:,2);
n=4;
np=80;
p=polyfit(xdata,ydata,n);
trec1=polyval(p,sr);
trec2=str2double(get(findobj('tag','edit12'),'string'));
if trec2>0
    trec=(trec1+trec2)/2;
    set(findobj('tag','edit12'),'string',num2str(trec));
else
    set(findobj('tag','edit12'),'string',num2str(trec1));
end
```

Z_g:

```
%calculate depth of the interface
trec=str2double(get(findobj('tag','edit12'),'string'));
pos=1;
num=size(M(:,1));
for pos=1:num
    xg= M(pos,1);
    tf= M(pos,2);
    tr= N(pos,2);
    tm= tf-tr-trec;
    tp= tf+tr-trec;
    zg= v1*tp/(2*cos)+sd+(gd-sd)/2;
    handles.fnldata(pos,1)= xg;
    handles.fnldata(pos,2)= zg;
end
```

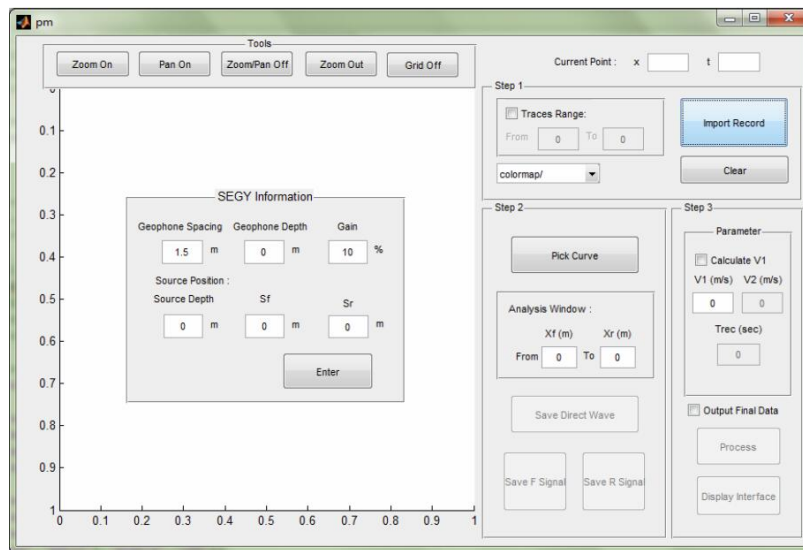**Layout of "pm"**

Initial interface of "pm" looks like this:

FIG. 9. Layout of "pm"

Operation instruction and its detail functions are demonstrated in Appendix.

FINITE-DIFFERENCE MODEL TESTS

To test "pm", we used 2-D finite-difference method to build single irregular interface model. Two most common circumstances has been tested: inclined layers and randomly undulating layers which both has 1km/s upper layer velocity and 3km/s lower layer velocity.

Inclined layers

Shots

Figure 10 is showing one pair of shots among all shot records.
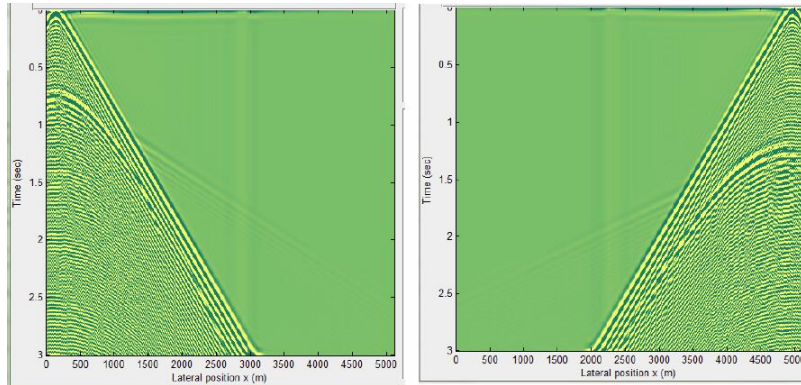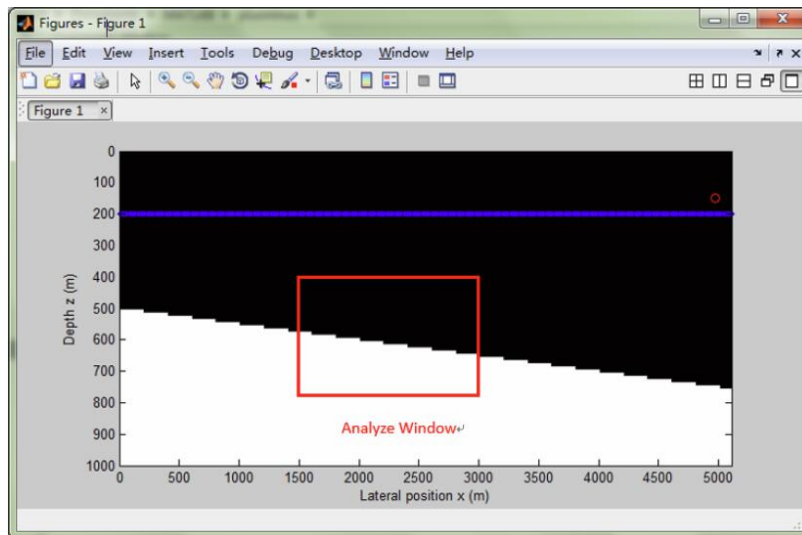

FIG. 10. Down/up dip shot record at inclined layers
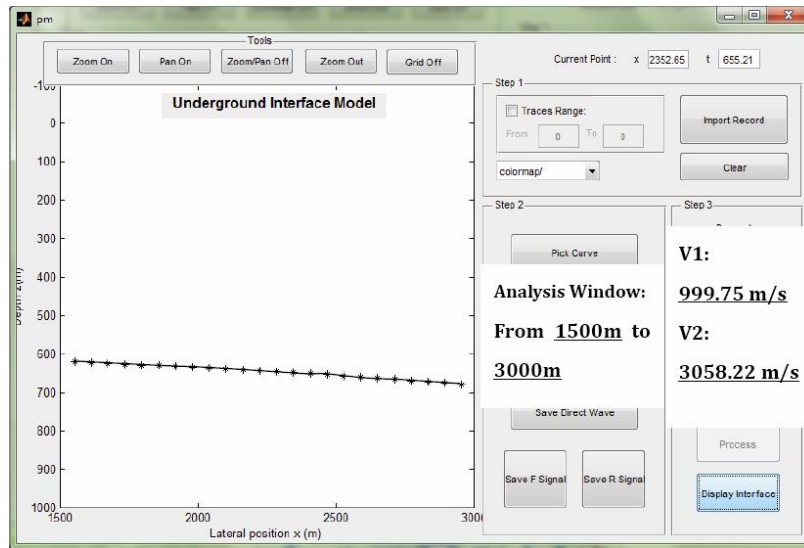

FIG. 11. Tomography of inclined layers

Result

FIG. 12. Result of 'pm' for single inclined interface
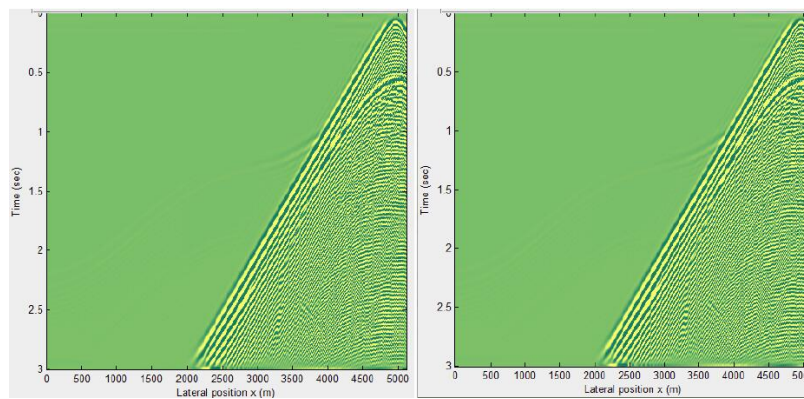
Randomly undulating layers

Shots
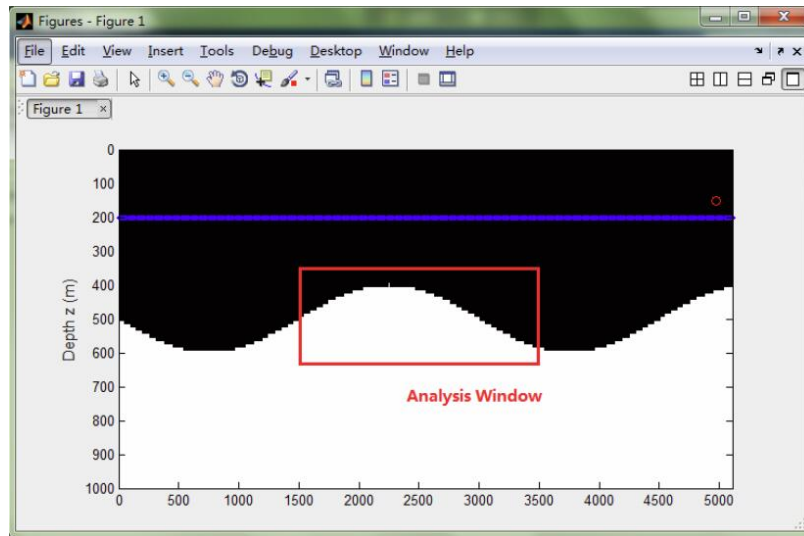

FIG. 13. Down/up dip shot record at undulating layers
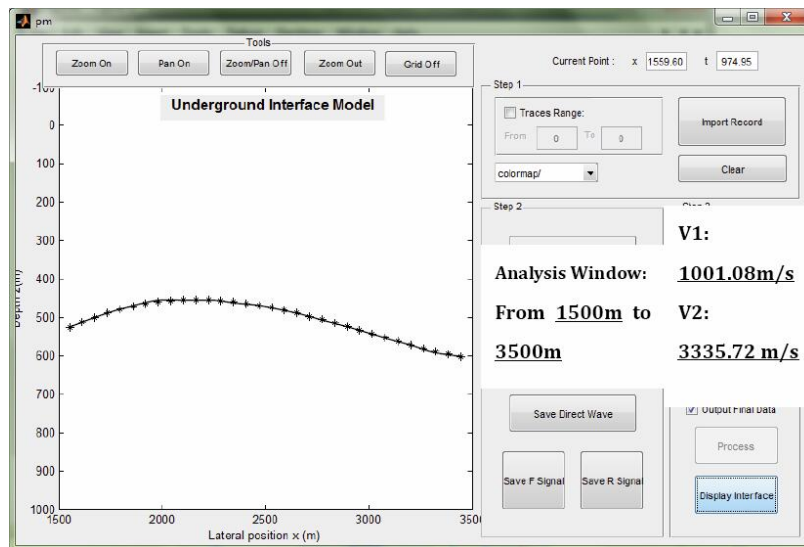
FIG. 14. Topography of undulating layers

Result

FIG. 15. Result of 'pm' for undulating interface

As shown above, "pm" reconstructed the interfaces in a fairly well manner with right depth position and identical trend as in the 2D models. However, the estimated velocities presented relatively big errors which are probably introduced by the hand-picking procedure. It is foreseeable that before replacing the hand-picking procedure with other automatic method which has better accuracy, the error will be inevitable. Generally speaking, "pm" gives acceptable results.

FIELD DATA TESTS

To further study the practicality and veracity of "pm", we tested it with field data. 2D data from Blackfoot oilfield is chosen, which locates at 15km southeast of Strathmore,
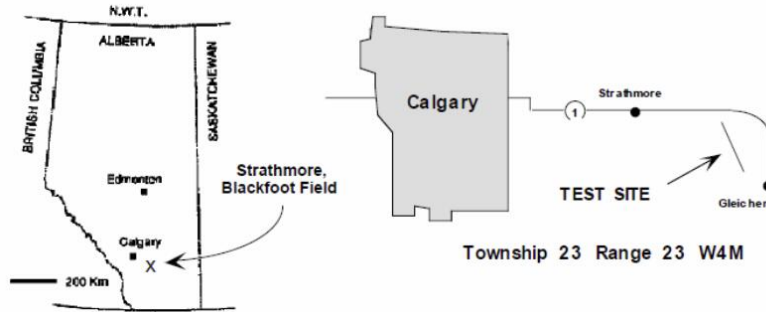
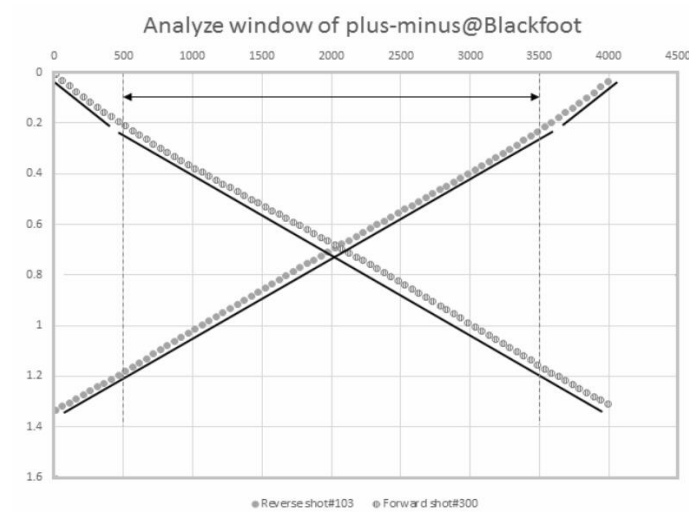FIG. 16. Location of Blackfoot oilfield and test line

FIG. 17. The manually picked up first arrivals from forward and reverse directions

Alberta (figure 16). The seismic line in this implementation is 4km long with receiver stations at every 20m and shot points in depth of 18m, at every half station. We took Dufour's research result (Dufour, 1996) of velocity and depth information over this field as a comparison.

Table 1. Geometry of the broad-band seismic line

Line length	4km (46km of cable)
Shot spacing	20m on the half station 6kg @18m
Peceiver spacing	20m
Line azimuth	Northwesterly $313°$

By picking first arrivals on each side, we were able to determine a reasonable analyze window for plus-minus calculation (figure 17).

"pm" accepts only single valued geophone depth input, which actually contravenes the natural condition as all earth surface has shifting elevation. In here we set all geophone depth as 0, so the result will not be interface elevation but thickness of its covering layer. Subtracting surface elevation data with covering layer thickness will present the final result. Figure 18 shows the thickness of first layer processed by "pm".
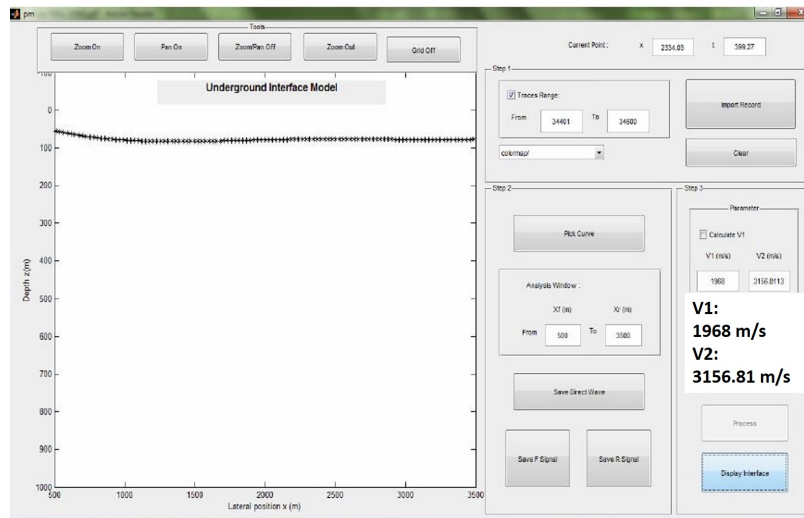
FIG. 18. The result of "pm"

Comparison between our result and P-wave depth model in Dufour's research are in figure 19. It proves "pm" can rebuild refractor at the right level. In both results the refractor is buried at about 840m in elevation while the surface ranging from 920m to 960m.

Notice that interface in figure 19(b) possesses more details than (a), that is because the plus-minus calculation is supposed to use variational velocities beneath different receivers, whereas in the principle of concision and speediness, our GUI uses unitary upper and lower medium velocities derived from fitting lines of direct wave and refraction. In here we input first layer velocity as 1968m/s according to Dufour. As a consequence, "pm" gave out the refractor velocity as 3156.81m/s, which is pretty close to Dufour's 3100m/s.

CONCLUSIONS

Hagedoorn's Plus-minus method is an effective and convenient tool to collect underground information of undetected region. The main idea is to get refractor velocity from minus time and covering layer thickness from plus time. It is applied in region that under coverage of both forward and reverse shots (i.e. in analyze window) and in some degree only suitable to two strata, single interface model. Although there are many factors that prevent it from being super accurate, it offers geophysicists an effective way of overviewing subsurface structure and help predicting the general range of underground characteristics, which are especially useful at the beginning of investigating an unidentified region and to help locate other more precise exploration methods.

From above tests, we can say that generally, the realization of plus-minus method in Matlab GUI is successful. "pm" is able to recover the interface depth and trend of both 2D finite-difference model and field data, and provide acceptable velocity estimations. Considering it is just a small tool aiming at people who would like to experience the convenience of plus-minus method, its achievements are adequate. Nevertheless, we believe that it has potentials to be improved to handle more complicated circumstance such as varying surface elevation and velocity.
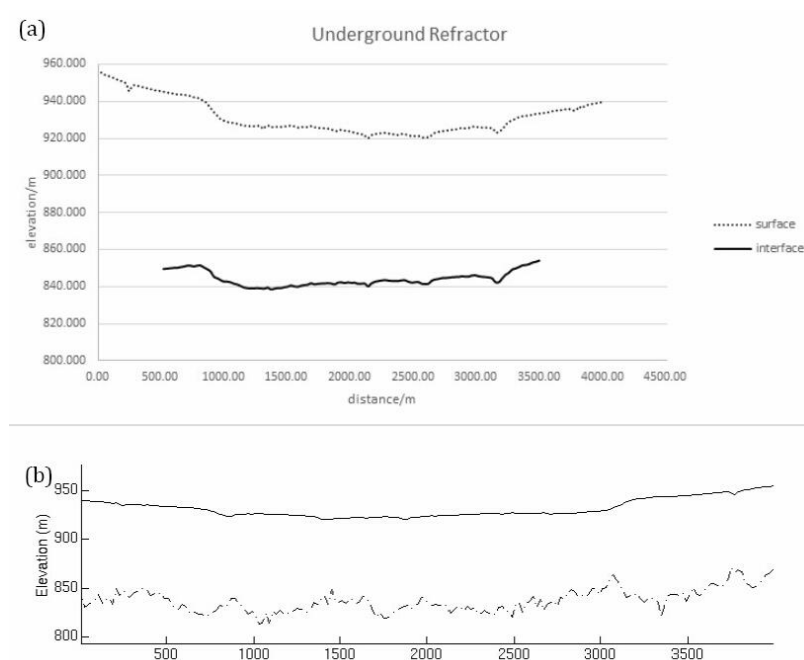
FIG. 19. Comparison between results of "pm"(a) and Dufour's research(b)

ACKNOWLEDGEMENTS

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APPENDIX: USER MANUAL FOR MATLAB GUI <PLUS-MINUS>

Purpose

This Matlab GUI is built on plus-minus time analysis method of refraction data of Hagedorn (1959). The main function of this tool is to pick the refraction data in seismic records, then rebuild and display the underground interface.

Notes

- Make sure you have installed CREWES Matlab toolbox
- Put the segy files you are going to use under the same path of this tool
- Only one underground interface can be processed each time

Warning

Since all the resample and calculation are based on the refraction data that is manually picked, and due to limitation of curve fitting in Matlab, the errors of the final results vary with operators and time. The results (including depth of the interface and lower medium velocity V2, etc.) cannot be identical to the theoretical values.

Users can improve the accuracy of the results by inputting upper medium velocity V1 and narrowing down the analysis window.

Steps

1. Running the tool

Put the "m" file and "fig" file under the same path, run either one to initialize the tool. It can be maximized.

2. Importing objective segy file

Click "Import Record" button, input geophone spacing and depth, source positions of the forward/reverse records as well as gain value for the pending image in the popped up "SEGY Information" panel.

Choose a file after "Enter".

If you want to import the record in a specific trace range, check the box "Traces Range:" and then input value. You can also change colormap below, the default colormap is "summer". Always do these before importing record or they will not be functioning.

3. Picking refraction data

Use "Pick Curve" button, click points on the curve you want to collect data from, once finish, press MB3 and then any key to end.

4. Saving data

If you want to calculate V1 value instead of inputing it manually, you will have to pick and save direct wave data first.

The analysis window—the range of the rebuilt interface you want to get from (Xf and Xr under "Pick Curve")—has to be input before saving any refraction data. After that, save data to the file you are working within.

5. Processing data

Click "Process" button to get results by plus-minus method, values of V2 and Trec with be calculated and displayed automatically.

Check "Calculate V1" box to get V1 automatically, or you will have to input the value before processing.

6. Displaying interface

When it shows on the command window that data is processed successfully, click "Display Interface" button to view the recovered interface model (or thickness of its covering layer if the surface is not horizontal).

7. Additional functions

1) In the "Tools" panel above the displaying region, "Zoom on" to help pick the signal more precisely, "Pan on" to move the image, "Zoom/Pan off" to enable the "Pick Curve" button, "Zoom out" to return to the original view, "Grid off" to help locate Xf and Xr.

2) "Clear" button will clean all the image and data except Trec (for the continuity from the forward record to reverse record).