

**Uncertainty Analysis of Direct Arrival Picks:
Applications in Eastern Saudi Arabia**

BY

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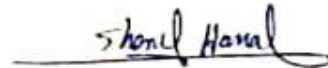
This thesis, written by **HASHIM M AL MUSAWI** under the direction of his thesis advisor and approved by his thesis committee, has been presented and accepted by the Dean of Graduate Studies, in partial fulfillment of the requirements for the degree of **MASTER OF SCIENCE IN GEOPHYSICS**.



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To my first teachers, my great parents |

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LIST OF ABBREVIATIONS

RU: Relative Uncertainty

VU: Velocity Uncertainty

AVG: Average

|

ABSTRACT

Full Name : [Hashim Mustafa Y Al Musawi]

Thesis Title : [Uncertainty Analysis of Direct Arrival Picks: Applications In Eastern Saudi Arabia]

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Error analysis is an essential part of any scientific experiment. Therefore, numerous techniques have been developed to determine uncertainties. The purpose of this study is to show how to quantify uncertainties in direct arrival picks and utilize error propagation analysis to estimate uncertainties in velocities calculated from these picks. This study also provides applications of quantitative determination of uncertainties in direct arrival picks and offsets on synthetic as well as two real seismic data sets from the eastern province of Saudi Arabia.

In one case study, the method is applied to a high-resolution shallow seismic refraction survey data in which only time is considered as an independent variable. The highest relative uncertainty percentage of velocity in this case is around 20%.

In the other case study, the technique is performed to a conventional seismic refraction data where both time and offset are independent variables. The highest relative uncertainty percentage of velocity is about 14%. |

ملخص الرسالة

الاسم الكامل: هاشم مصطفى ياسين الموسوي

عنوان الرسالة: تحليل عدم اليقين في أوقات الوصول المباشرة المنتقاة: تطبيقات في شرق المملكة العربية السعودية

التخصص: جيوفيزياء

تاريخ الدرجة العلمية: أكتوبر 2020

يعد تحليل الأخطاء جزءاً أساسياً من أي تجربة علمية. لذلك، تم تطوير العديد من التقنيات لتحديد أوجه عدم اليقين. وإن الغرض من هذه الدراسة هو توضيح كيفية حساب عدم اليقين في انتقاء أوقات الوصول الأولى واستخدام معادلات تراكم الخطأ لتقدير الأخطاء في السرعات المحسوبة من هذه الإنتقاعات. وتقدم هذه الدراسة أيضاً تطبيقات للحسابات الكمية للأخطاء في انتقاء أوقات الوصول المباشرة والأبعاد لبيانات اصطناعية ومجموعتين من البيانات الحقيقية التي تم الحصول عليها من خلال مسح أجزاء من المنطقة الشرقية في المملكة العربية السعودية.

في الحالة الأولى، تم تطبيق الطريقة على بيانات مسح زلزالي انكساري ضحل وعالي الدقة والتي يعتبر فيها الوقت فقط متغيراً مستقلاً. وأعلى نسبة خطأ نسبي للسرعة تم الحصول عليها في هذه الحالة 20٪ تقريباً.

أما في الحالة الأخرى، يتم تنفيذ الطريقة على بيانات زلزالية انكسارية لمنطقة ضحلة بحيث يكون كل من الوقت والإزاحة متغيرين مستقلين. وفي النهاية، كانت أعلى نسبة خطأ نسبي للسرعة لهذه الحالة هي حوالي 14٪.

CHAPTER 1

INTRODUCTION

Error analysis has become an essential component of any scientific research or experiment. Errors can be divided in two main categories: Instrumental and statistical. Uncertainties in measurements that arise from fluctuations in instrumental readings are instrumental errors. On the other hand, errors coming from collection of finite data over finite intervals are called statistical errors (Bevington & Robinson, 1992). The two types of errors must be identified to obtain accurate results in any scientific experiment, even if these errors are small as they may grow during the experiment.

In many experiments we make different measurements to calculate a certain value called dependent variable. The dependent variable is determined from a set of measurements which may include some uncertainties, leading to a greater error in the calculated value. Carrying over the uncertainties to the dependent variables is called error propagation. As a part of error analysis, error propagation should be considered.

In geophysical methods, there are many stages in which errors may arise, during acquisition from instrument readings, inaccurate layout settings, incorrect parameters and so on. Moreover, there are many errors that result from first arrival picking, velocity analysis and different calculations during the processing and interpretation phases.

One of the most important techniques in geophysics is the seismic refraction method. It has been used mainly for two types of problems: shallow structures

determination and characterization of crustal-scale velocity structure. Despite the interest of data analysis in these areas, errors and uncertainties estimation in forward modeling need to be improved. This has become a major challenge in seismic works (Liu & Stock, 1993).

One of the primary stages in seismic refraction method is velocity determination. Velocity is a dependent variable and can be calculated from first arrival picks and offsets. Therefore, uncertainties in first arrival picking and offsets will propagate to velocity, which will be the main concern in this study. I will provide applications of error propagation formulas on uncertainties that arise from inaccurate direct arrival picking and offsets to estimate the propagated uncertainties in velocity of the direct arrivals.

1.1 Research Objective

This study involves three main objectives. First, it gives general idea about uncertainties quantification in first arrival picks, and utilization of error propagation formulas to estimate uncertainties in velocities calculated from these picks. Also, it provides applications of quantitative determination of uncertainties in direct arrival picks and offsets on synthetic as well as two real data sets from the eastern province of Saudi Arabia. For the scope of this thesis, I will focus on only velocities of direct arrivals.

1.2 Thesis Structure

This study consists of three main parts. The first is applying the methodology on synthetic data. The second stage is implementing the method on a high-resolution shallow seismic refraction survey data where the time is the only independent variable. Finally, applying the technique to shallow seismic refraction data where both the time and offset are independent variables. After completing the application of the three stages, results will be discussed. |

CHAPTER 2

LITERATURE REVIEW

A comprehensive discussion of error analysis including propagation of error has been presented by many studies (e.g., Bevington & Robinson, 1992; Baird, 1995; Taylor, 1997). Complexity of the problems, different accuracy required, and other factors result in developing different approaches to estimate error propagation. Evans (1972) and Taguchi (1987) used numerical integration-based methods to calculate error propagation.

On the other hand, Taylor series method has been used to estimate error propagation by Christensen (1982) and others. Furthermore, Hasofer & Lind (1974) used the most probable point approach to calculate error propagation. A simulation-based approach was used to estimate error propagation by Madsen et al. (2006). Many problems may arise using this method with variability of input or if the function is nonlinear (Chen, 2008). Polynomial chaos and Neumann expansions were used by Xiu (2003). These methods have begun to emerge significantly to estimate uncertainty. Other methods like Min-Max method has been used commonly to evaluate error propagation but this method usually overestimates the uncertainty (Deardorff, 2001).

The method used in this study is the general formula of error propagation (partial derivative approach), shown and derived in Bevington & Robinson (1992) and Taylor

(1997) among others. One reason to use this method is that a small change in a function with variables can be represented easily and accurately by derivatives. Also, most other methods are used in critical situations where the function cannot be derived; there are too many variables; standard deviation is not known or cannot be evaluated ...etc.; which are irrelevant cases in seismic refraction.

In this study, the function differentiation and standard deviation are easy to calculate, only one or few independent variables are required to estimate error propagation in velocity, and errors in the independent variables (i.e., time and offset) are small. Moreover, this method has been conventionally and frequently used by researchers in similar experimental setups.

The aim of this study is to show how to quantify uncertainties in direct arrival picks and offsets, and utilize error propagation formulas to estimate uncertainties in velocity. We apply the method for a quantitative determination of uncertainties in direct arrival picks and offsets on two shallow seismic refraction survey data sets from the eastern province of Saudi Arabia. Since the used method in this study is applied to seismic refraction data. Then, the main principle of seismic refraction method is explained briefly next.

Reynolds (2011) explains that seismic refraction method is based on the principle of the effect of velocity variation upon a boundary where the wave changes its direction as it enters the new medium. The contrast in seismic velocity upon the

boundary controls the amount of change in the direction of the seismic wave according to Snell's law.

When the source starts producing waves, the resulting waves travel in many directions including directly along the ground surface (direct waves), along the top of the refractor by critical refraction and from the top of the refractor by reflection (Figure 1). After that, waves will be recorded by a set of geophones, and the output of each one can be shown as a single trace. Offset of each geophone is known from layout of the survey and associated travel times can be measured to generate time-distance graph that is used to estimate velocities (Reynolds, 2011). Figure 2 shows an example of raw seismic shot gather with first arrivals picked where the direct and refracted first arrivals are labeled in green and red colors, respectively.

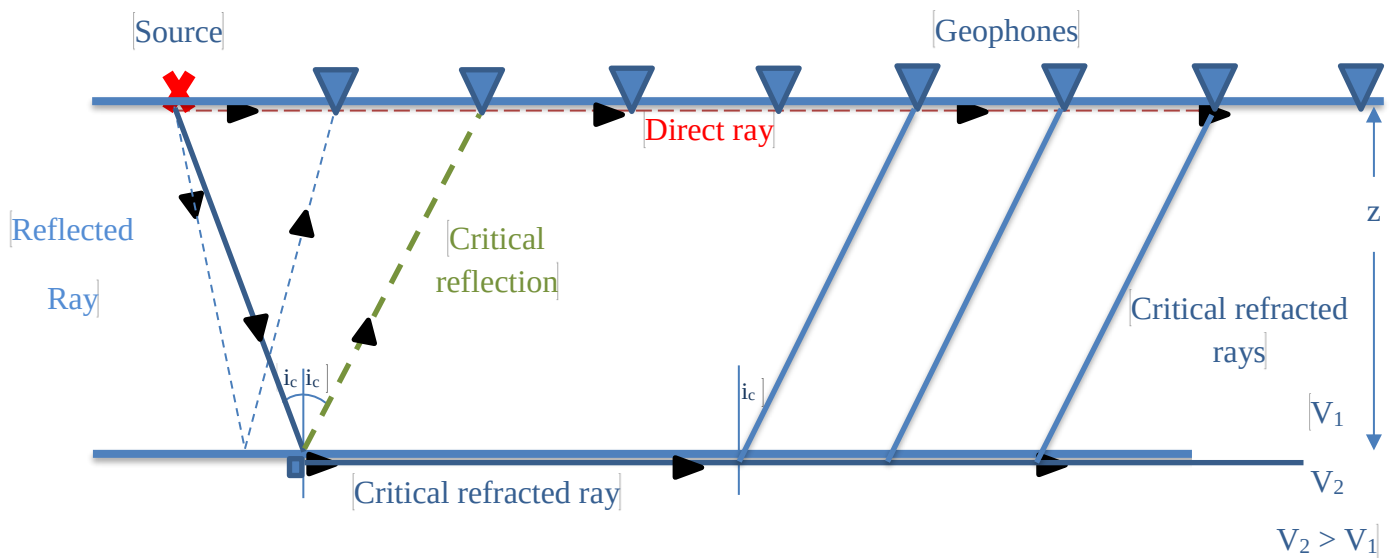


Figure 1. Ray path diagram for direct, refracted and reflected rays

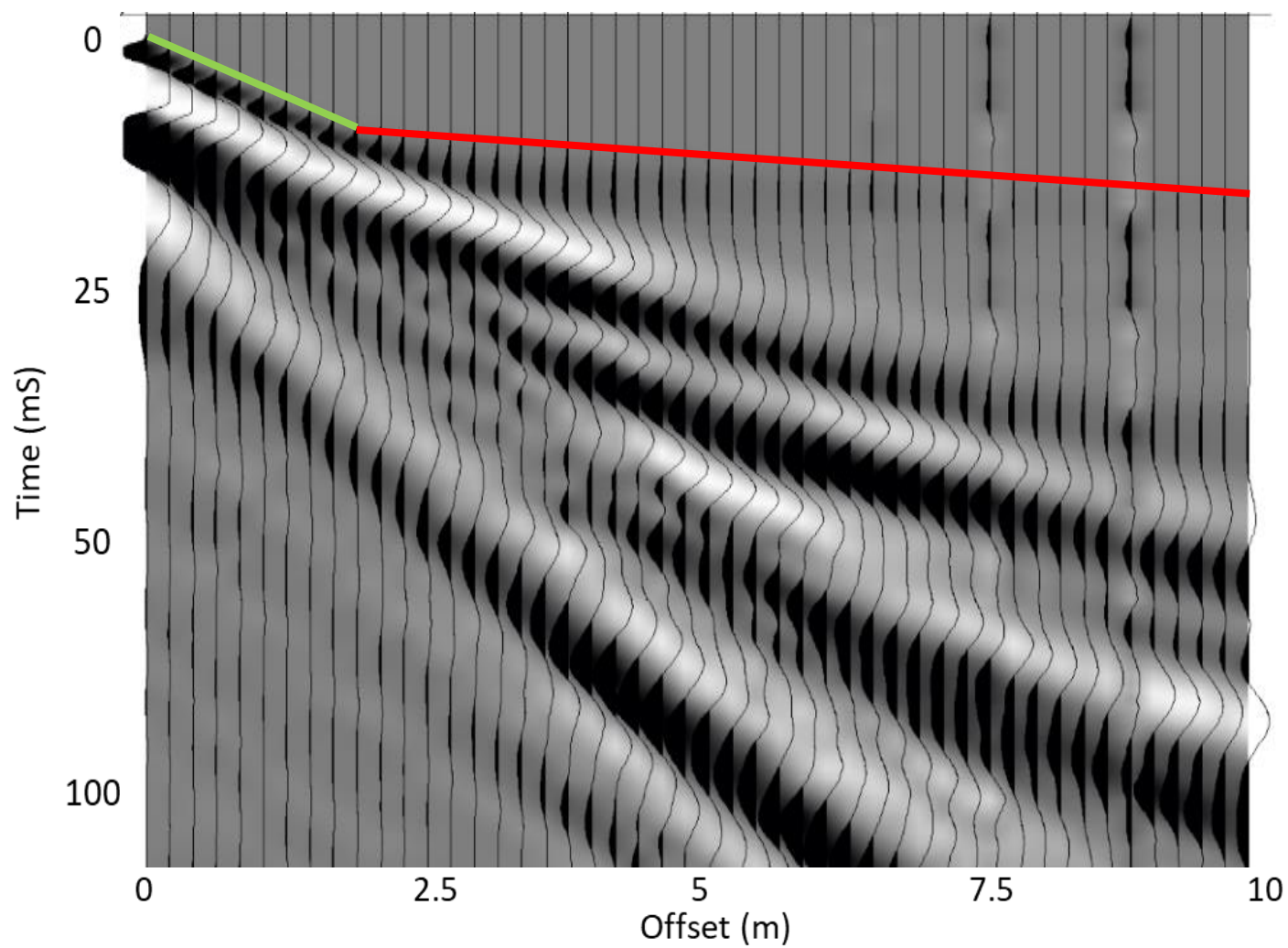


Figure 2. An example of raw seismic shot gather with first arrivals picked where the direct and refracted first arrivals are labeled in green and red colors, respectively

CHAPTER 3

METHODOLOGY

3.1 Error Propagation Analysis

As discussed before, the method that I will use to calculate uncertainties in this study is the general formula of error propagation (partial derivative approach). There are several operations and steps that must be performed to apply the error propagation formula as follows.

- (1) Data sortation. (A). When time is the only independent variable, data is sorted in sets such that each set represents direct-wave arrival picks (T) corresponding to the same source and receiver locations. Changes in time picks are attributed mainly to picking errors since the direct wave is not affected by tide. (B). When both time and offsets are independent variables, data will be sorted in sets such that each set consists of four first arrival picks (T) corresponding to the same offset (X) from the four end shots.
- (2) Mean, standard deviation and variance of direct-wave arrival picks are calculated. For the second case, these calculations will be implemented for the offsets as well since both (T) and (X) have different readings.
- (3) Relative uncertainty percentage (RU %) of direct-wave arrival picks and offsets are calculated.

- (4) Mean of all direct-wave velocities corresponding to the same shot location is calculated.
- (5) Identifying the dependent variable function.
- (6) Taking the partial derivative of the function with respect to the independent variables.
- (7) The general formula of error propagation (Bevington and Robinson, 1992) is applied as:

$$\delta f = \sqrt{\left(\frac{\partial f}{\partial x_1} \delta x_1\right)^2 + \left(\frac{\partial f}{\partial x_2} \delta x_2\right)^2 + \dots + \left(\frac{\partial f}{\partial x_n} \delta x_n\right)^2} \quad (1)$$

Where δf is the standard deviation of the function (f), δx_1 , δx_2 and δx_n are the standard deviation of the first, second and n^{th} independent parameter respectively.

- (8) Mean and standard deviation of velocities corresponding to the same shot and receiver locations are calculated. The mean velocity is considered as the true velocity value since it is the best estimate.
- (9) Writing the velocity in the final form as follows

$$V = \bar{V} \pm \delta V \quad (2)$$

Where $\bar{V}$ and δV are the true velocity and standard deviation of velocity, respectively.

- (10) The relative uncertainty percentage (RU%) of velocity is calculated as follows

$$RU\% = \frac{\delta V}{V} \times 100 \quad (3)$$

3.2 Synthetic data

The first step is to apply our methodology to synthetic data. The data model used in this study consists of two layers where the thickness of the first one is 0.5 m, and velocities of first and second layers are 300 m/s and 1100 m/s, respectively. Length of the receiver line was 13.4 m using 68 geophones with spacing of 0.2 m. Two symmetric shots located at the first and last receivers were used in this model.

For each of shots, the first arrival times were picked automatically (Figure 3) and plotted against offset to estimate the velocities of each layer. The estimated velocities for first and second layers are 280 m/s and 1113 m/s, respectively.

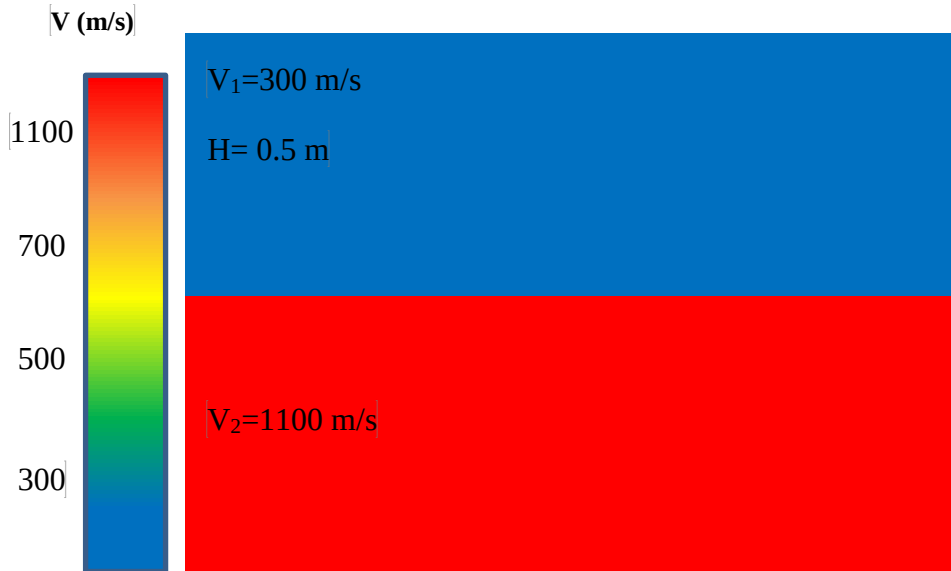


Figure 3 | Velocity model for synthetic data |

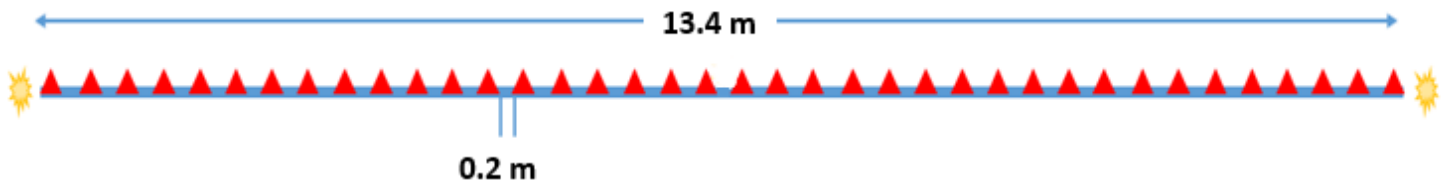


Figure 4 A sketch of the seismic line layout for the synthetic model

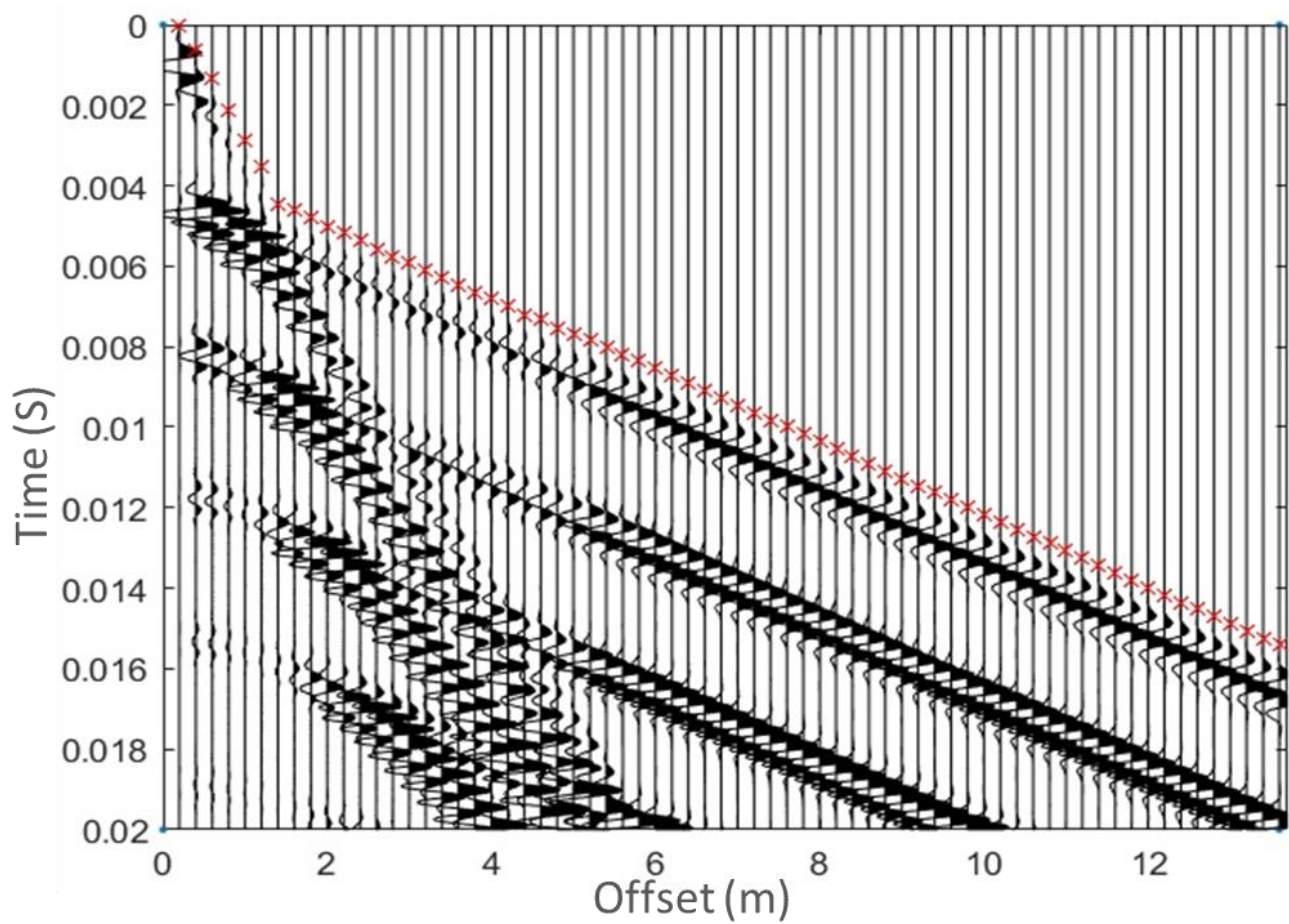


Figure 5. First seismic shot generated using synthetic data. Crosses indicate the first arrivals picks.

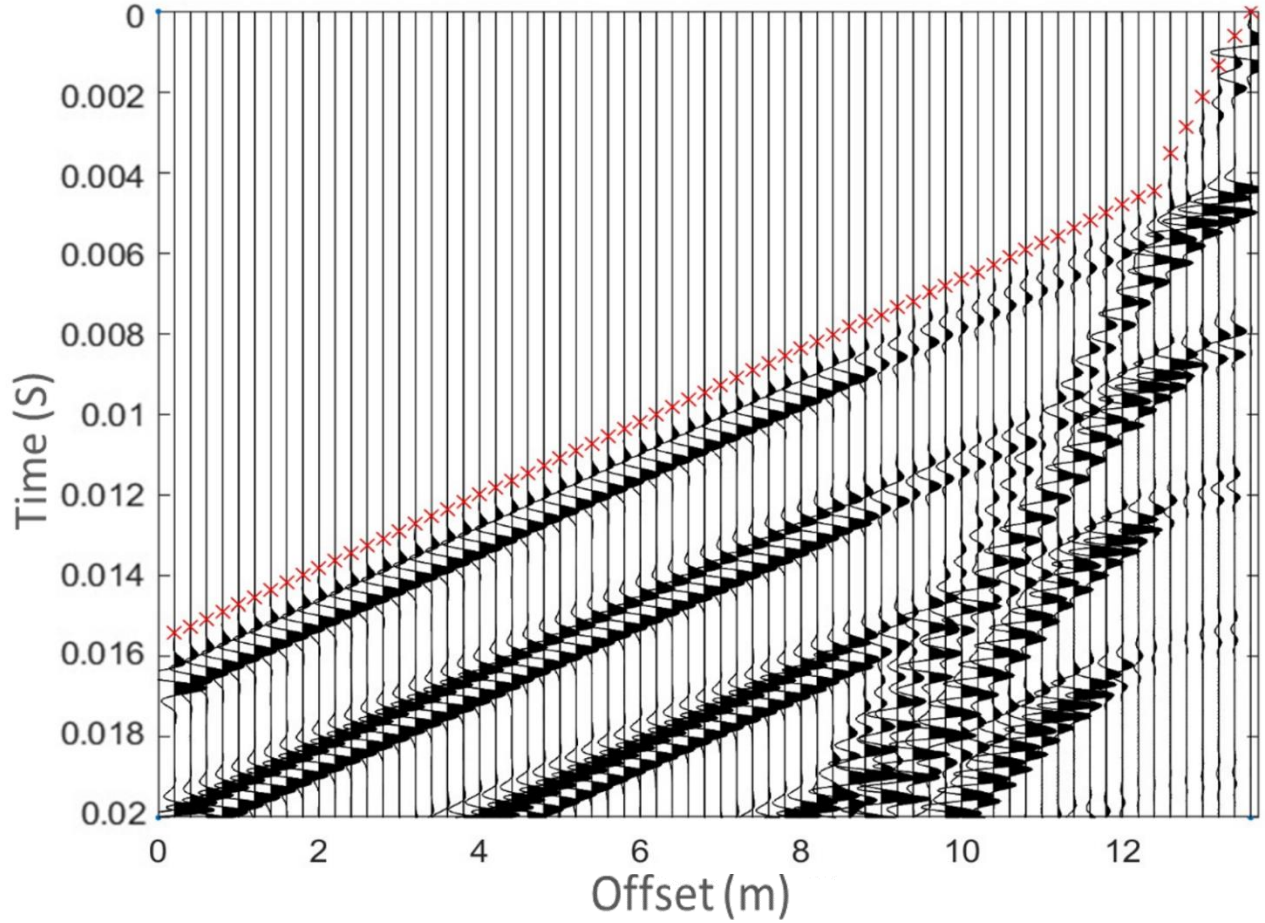


Figure 6 Second seismic shot generated using synthetic data. Crosses indicate the first arrivals picks.

The following procedure will be used to estimate uncertainties and error propagation for the synthetic data:

- (1) Estimated velocity is calculated based on first arrival picks (T).
- (2) The dependent variable function is:

$$V(T) = X/T \quad (4)$$

Where V is the direct-wave velocity calculated using travel times (T) picked at different times and X is the fixed offset.

- (3) Uncertainty in velocity is calculated from the true velocity, which is known in this case.

$$\delta V = \sqrt{\left(\frac{\partial V}{\partial T} \delta T\right)^2 + \left(\frac{\partial V}{\partial X} \delta X\right)^2} \quad (5)$$

Where δV is the standard deviation of the velocity (V), δT , δX are the standard deviation of the time and offsets parameters respectively.

- (4) Velocity value in the final form as formula (2):

$$V = \bar{V} \pm \delta V$$

Where $\bar{V}$ and δV are the true velocity and standard deviation of velocity, respectively.

- (5) The relative uncertainty percentage (RU %) of velocity is calculated as formula (3).

$$RU\% = \frac{\delta V}{\bar{V}} \times 100$$

3.3 Case Study I

In this case study, the aim of the survey was to monitor water table depth change in a beach sand due to tide using a high-resolution shallow seismic refraction survey. The experiment took place at KFUPM beach as shown in Figure 8. Length of the receiver line was 9.4 m using 48 geophones with a spacing of 0.2 m (Figure 7). The line was parallel to the shoreline and almost 5 meters away from the high tide mark. Five shots were acquired, two end shots at each end of the line and one middle shot. The five-shot survey was repeated six times over 12 hours (one tidal cycle).

For each of the six surveys, the first arrival times on all five shots were picked manually and plotted against offset to estimate the velocity and the thickness of the beach sand layers. Fig 9-14 show seismic shots repeated from the same location (0.5 m at the left of the line). The velocity of the unsaturated sand was in the range of 200-400 m/s. For the saturated sand layer, the velocity was between 900-1300 m/s. The average velocities from the five shots were used to estimate water table depth. The sea level was monitored in a borehole located on the survey line over a 12-hour cycle to be used as a reference for the water table depth estimation from seismic data. Finally, the water table depth in the borehole ranged between 51-76 cm over the 12-hour cycle.

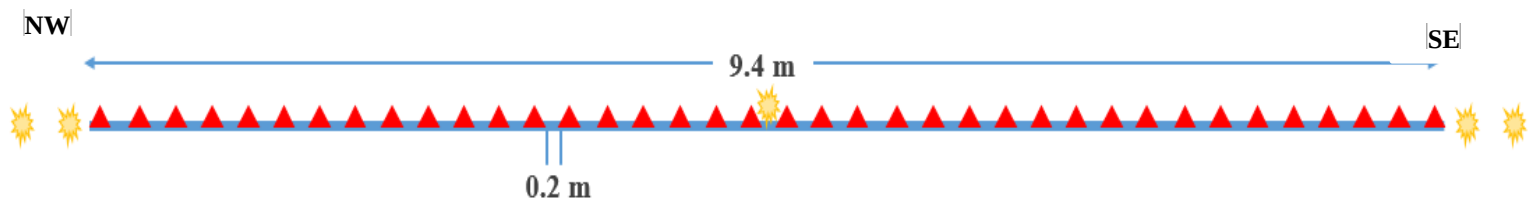
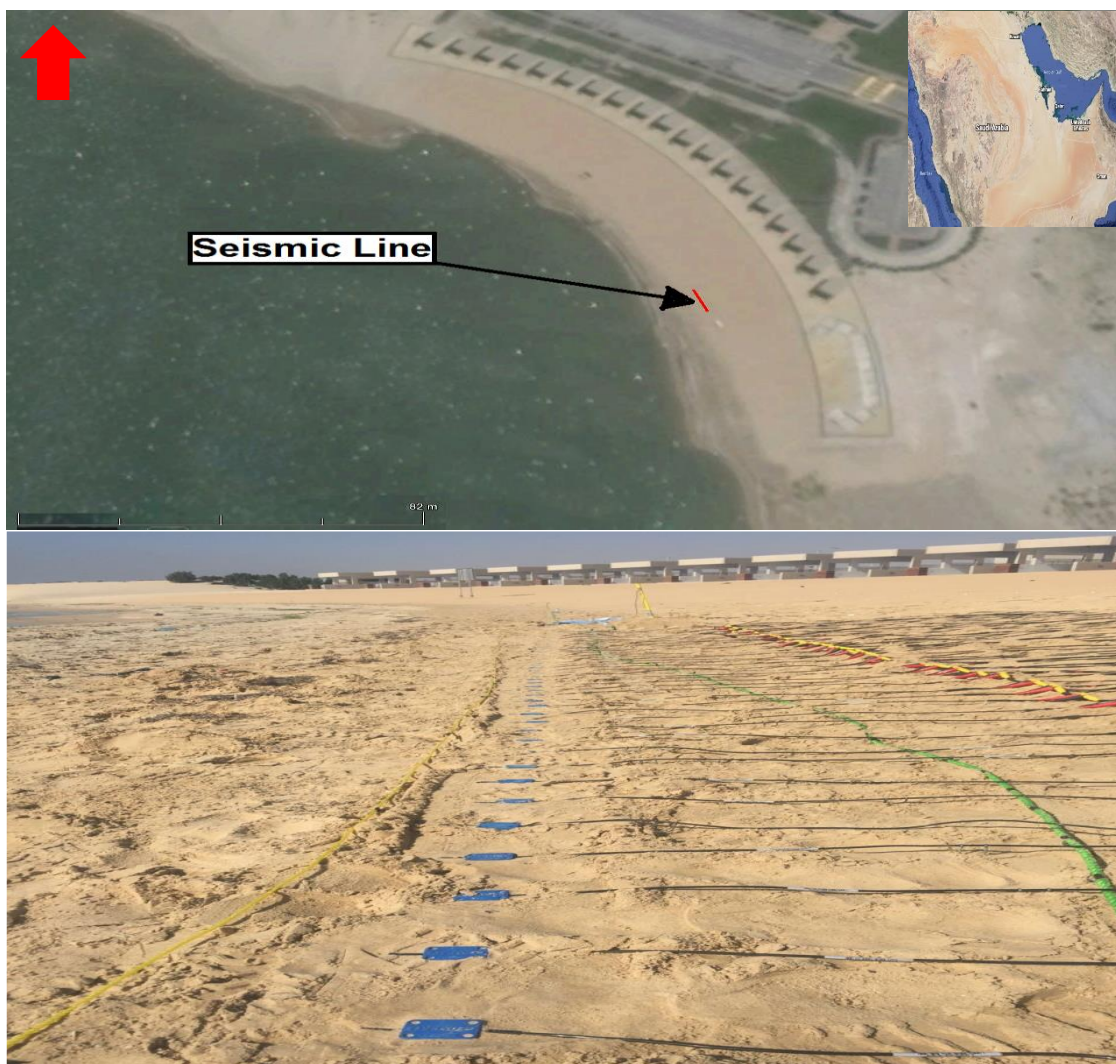


Figure 7. A sketch of the seismic line layout with the five shot locations.



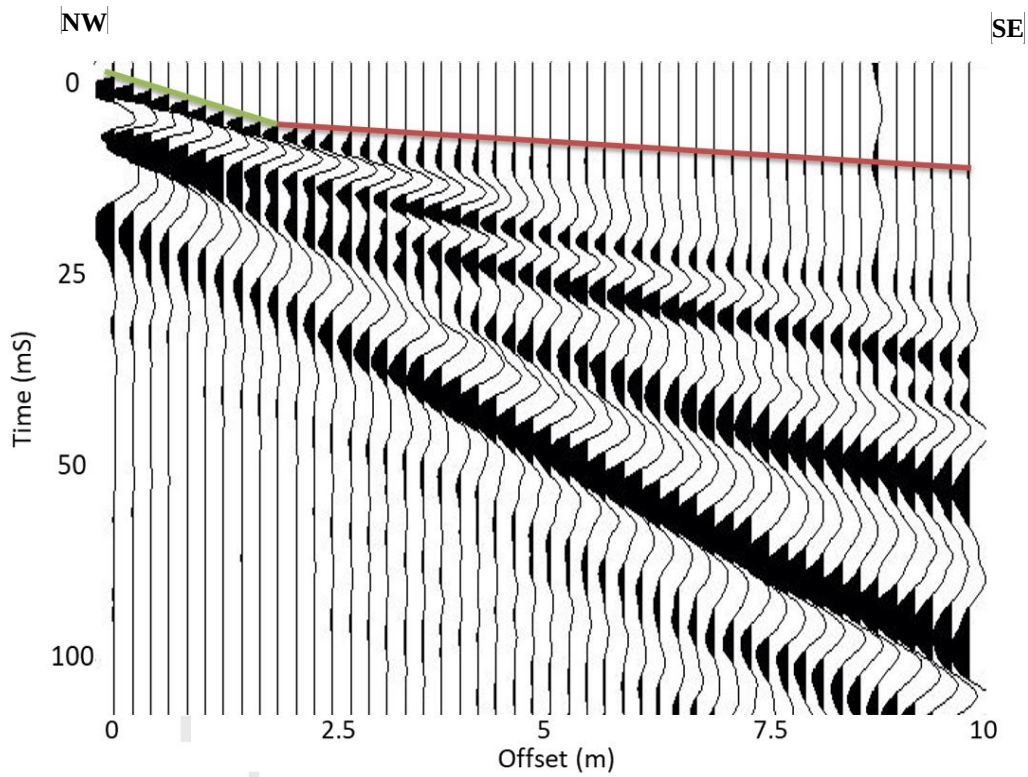


Figure 9 First seismic shot 0.5 m at the left of the line with indication of the direct (green) and refracted (red) first arrivals

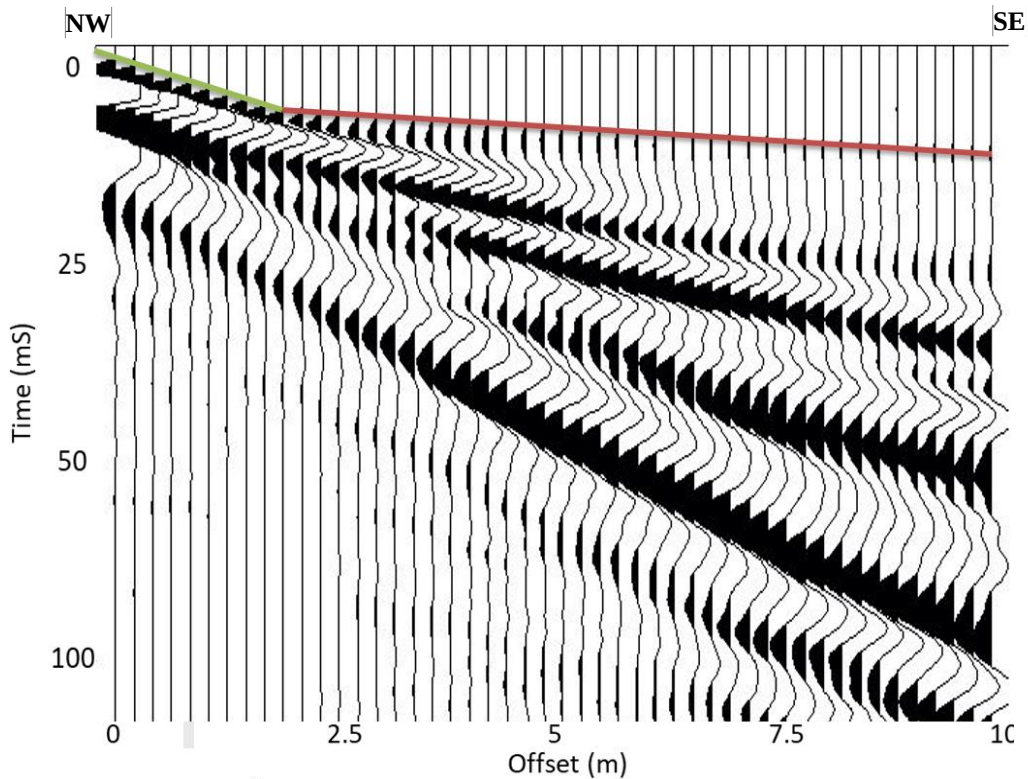


Figure 10. Second seismic shot 0.5 m at the left of the line with indication of the direct (green) and refracted (red) first arrivals

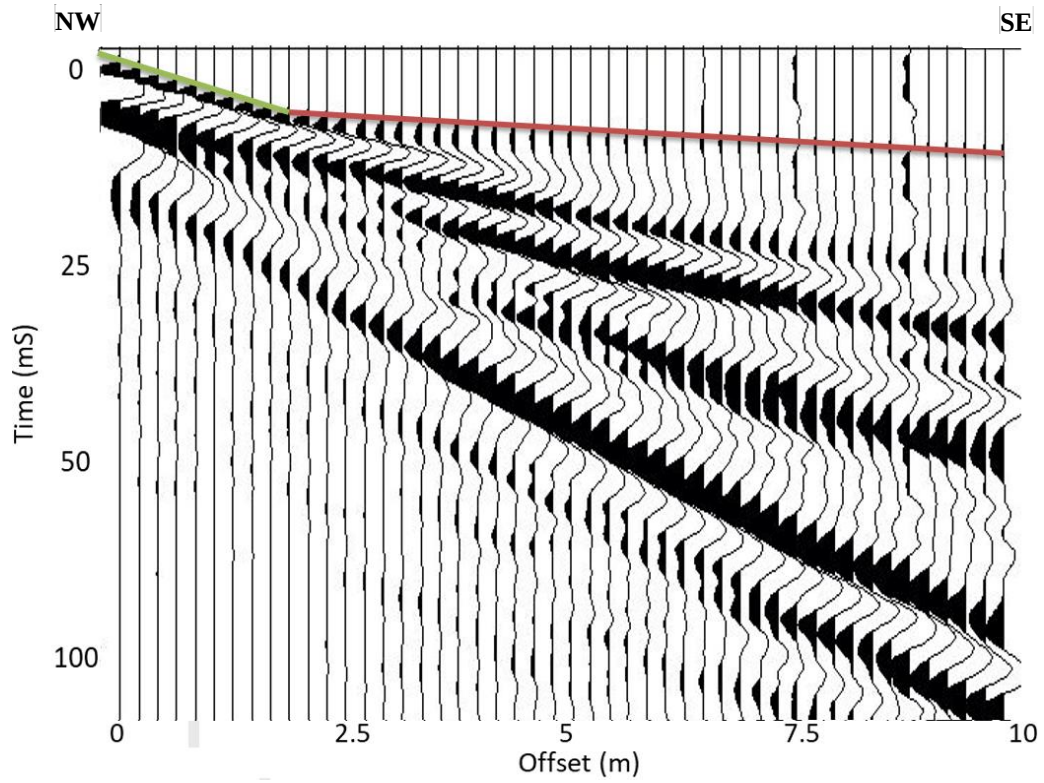


Figure 12 Third seismic shot 0.5 m at the left of the line with indication of the direct (green) and refracted (red) first arrivals

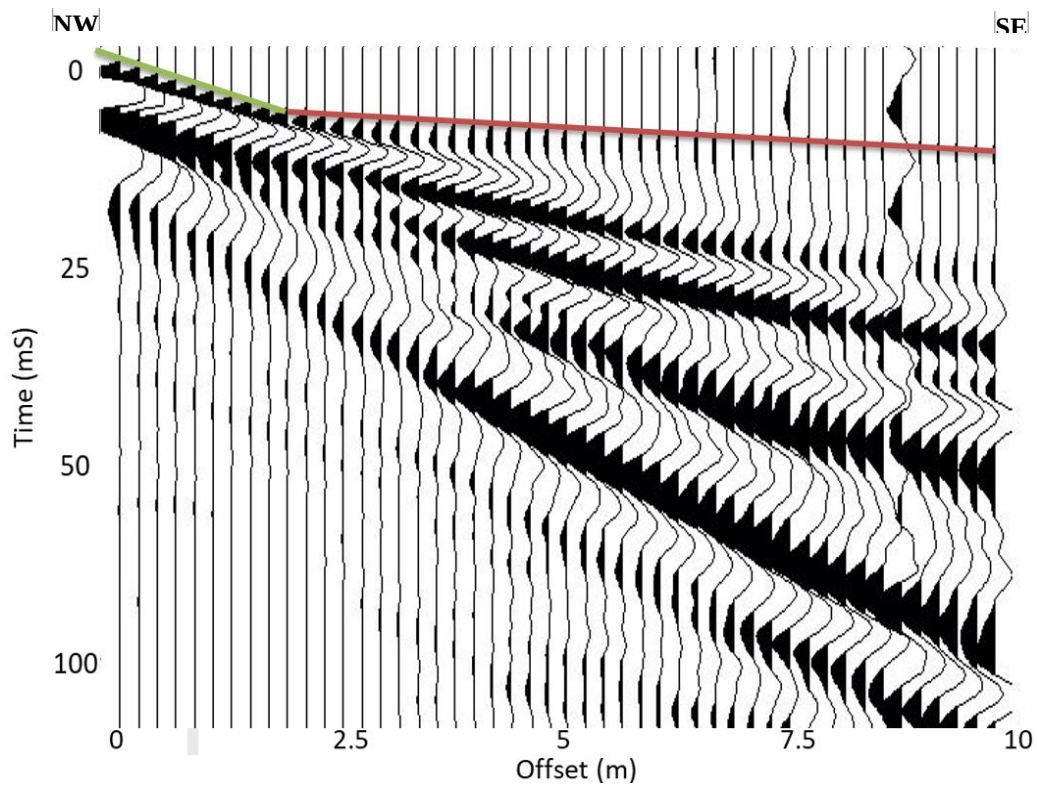


Figure 11 Forth seismic shot 0.5 m at the left of the line with indication of the direct (green) and refracted (red) first arrivals

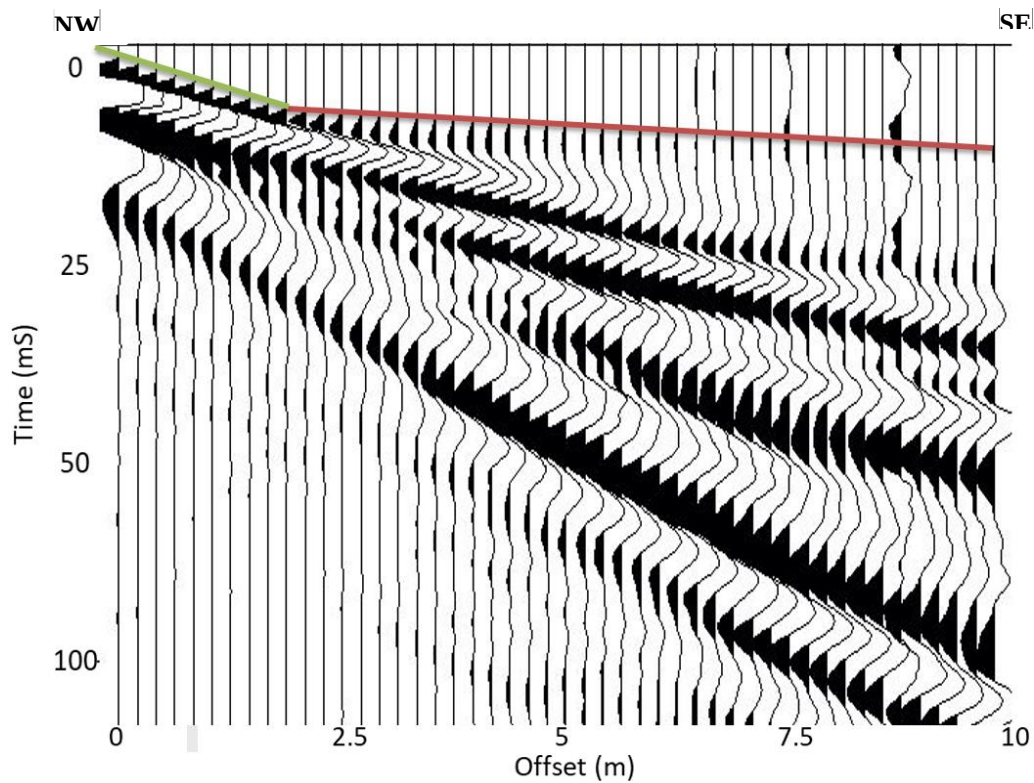


Figure 13 Fifth seismic shot 0.5 m at the left of the line with indication of the direct (green) and refracted (red) first arrivals

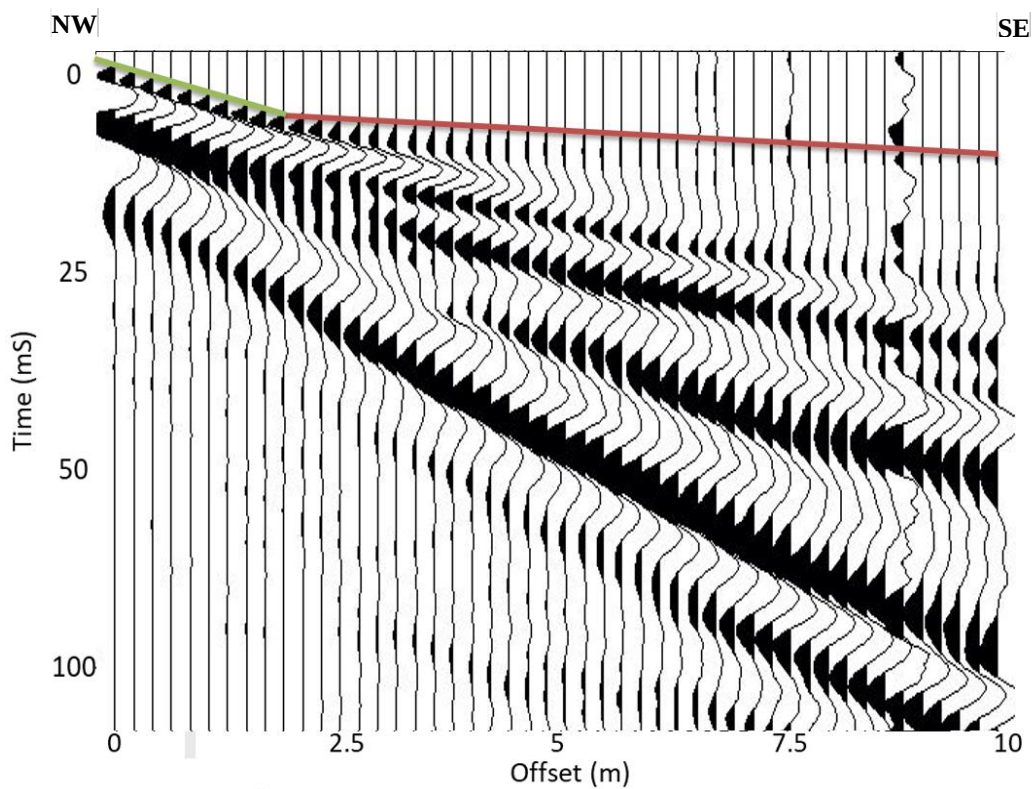


Figure 14 Sixth seismic shot 0.5 m at the left of the line with indication of the direct (green) and refracted (red) first arrivals

The following procedure will be used to estimate uncertainties and error propagation for the case when direct-wave arrival time is the only independent variable:

- (1) The data is sorted in sets such that each set represents direct-wave arrival picks (T) corresponding to the same source and receiver locations. Changes in time picks are attributed mainly to picking errors since the direct wave is not affected by tide.
- (2) Offset is assumed to be constant since no source or receiver was moved in each set of traces.
- (3) Mean, standard deviation and variance of direct-wave arrival picks will be calculated.
- (4) Relative uncertainty percentage (RU%) of direct-wave arrival picks is calculated.
- (5) Mean of all direct-wave velocities corresponding to the same shot location is calculated.
- (6) The dependent variable function (4) is:

$$V(T) = X/T$$

Where V is the direct-wave velocity calculated using travel times (T) picked at different times and X is the fixed offset.

- (7) The result of partial differentiation of V with respect to time is:

$$V'(T) = -X/T^2 \tag{6}$$

Where T is the mean of six travel times picked at offset X during the 12-hour tide cycle.

- (8) The general formula of error propagation (formula 1) is applied. Since the only varying independent variable is time, the application of the formula will be as follows :

$$\delta V = \sqrt{\left(\frac{\partial V}{\partial T} \delta T\right)^2} \quad (7)$$

Where δV is the standard deviation of the velocity (V) and δT is the standard deviation of the time.

- (9) Mean and standard deviation of velocities corresponding to the same shot and receiver locations is calculated. The mean velocity is considered as the true velocity value since it is the best estimate.

- (10) Velocity value in the final form (formula 2):

$$V = \bar{V} \pm \delta V$$

Where $\bar{V}$ and δV are the mean and standard deviation of velocity, respectively.

- (11) The relative uncertainty percentage (RU%) of velocity is calculated as formula (3)

$$RU\% = \frac{\delta V}{\bar{V}} \times 100$$

3.4 Case Study II

In this case study, the aim of the survey was to map the water table below a sand dune using a conventional seismic refraction survey. The experiment took place at KFUPM beach as shown in Figure 15. Length of the receiver line was 115 m using 24 geophones with spacing of 5 m. Five shots were acquired, two end shots at each end of the line and one middle shot (Figure 16). A differential global positioning system device (DGPS) was used to measure the elevations at the shot and geophone locations. Figure 17-20 shows seismic shots of this dataset. The first arrival times on all five shots were picked manually and plotted against offset to estimate the velocity.



Figure 15. Seismic line location over the sand dune at KFUPM Beach

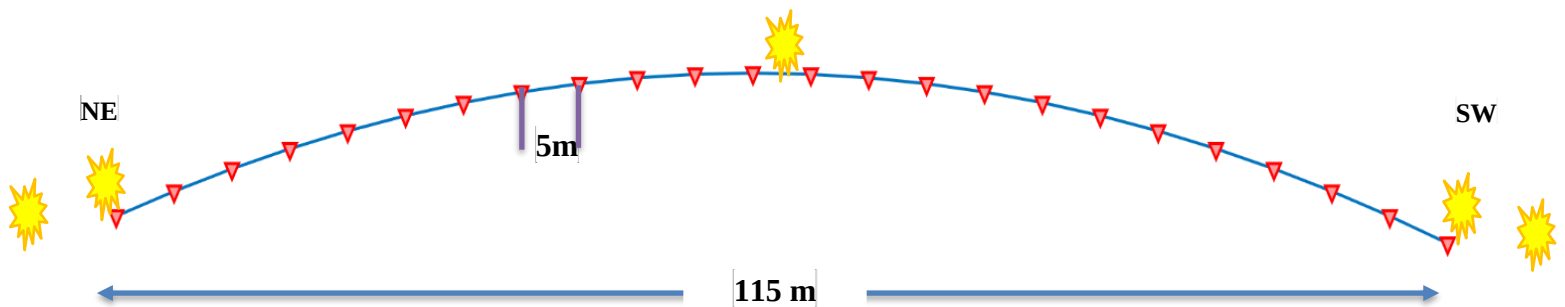


Figure 16. Sketch of the seismic line layout over the sand dune with the five shot locations

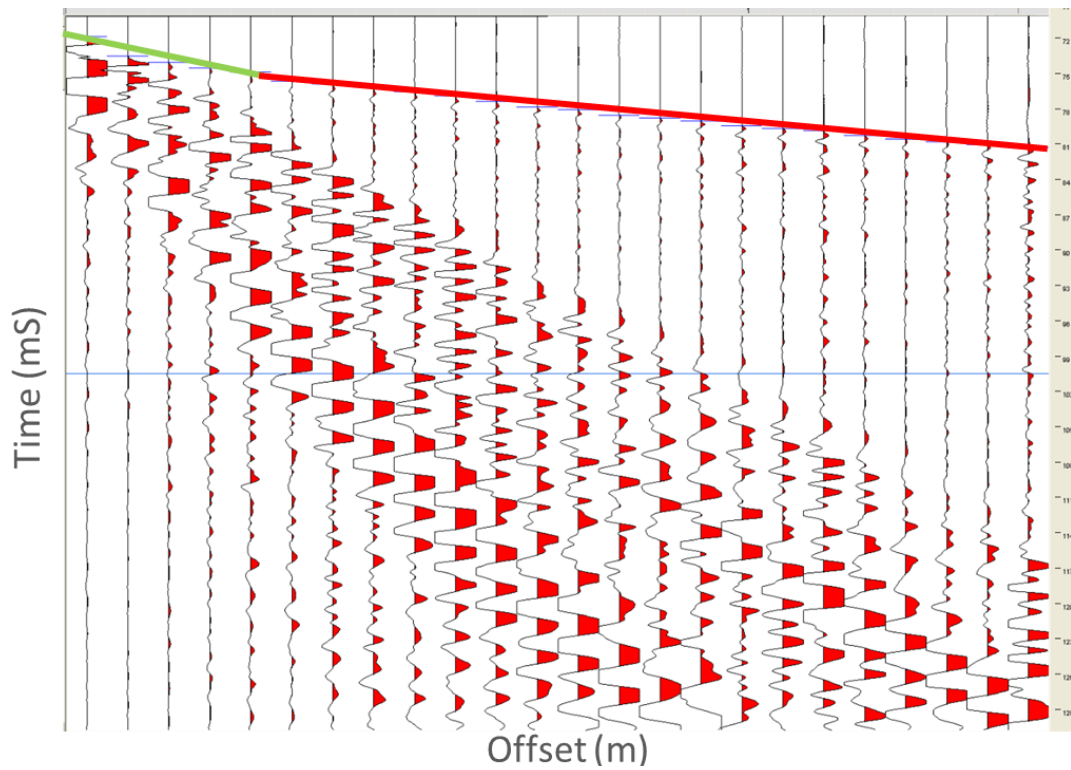


Figure 18 Seismic shot with source to the left of the line with indication of the direct (green) and refracted (red) first arrivals

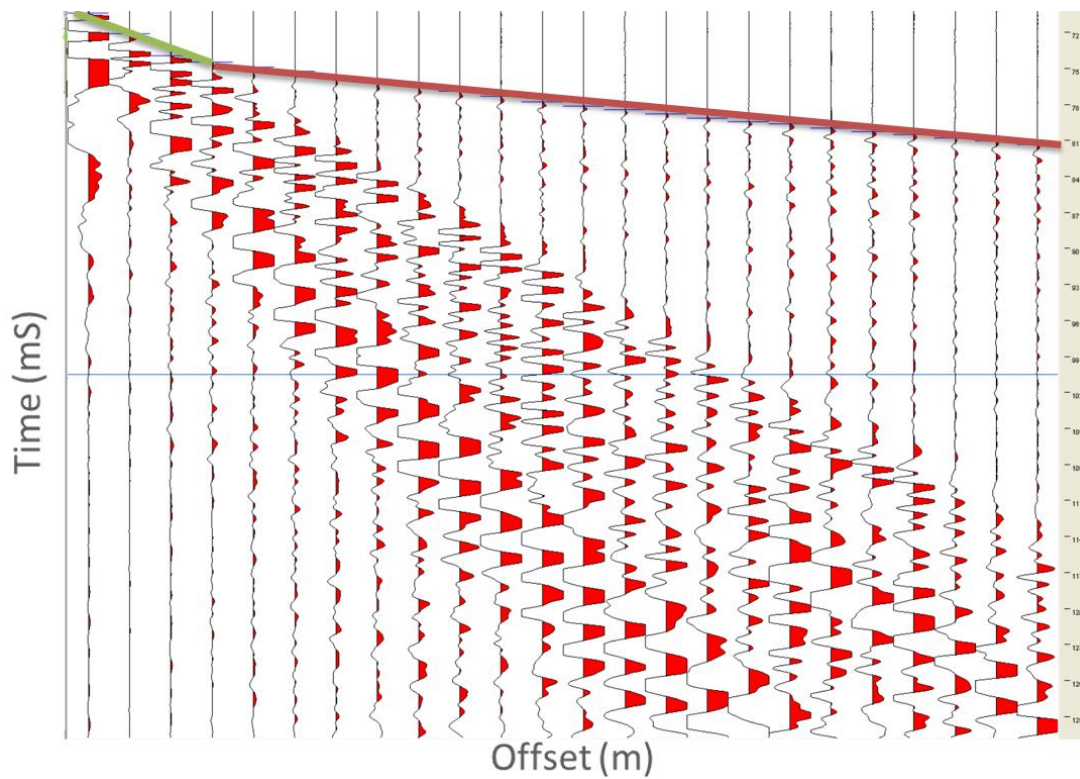


Figure 17 Seismic shot with source to the left of the line with indication of the direct (green) and refracted (red) first arrivals

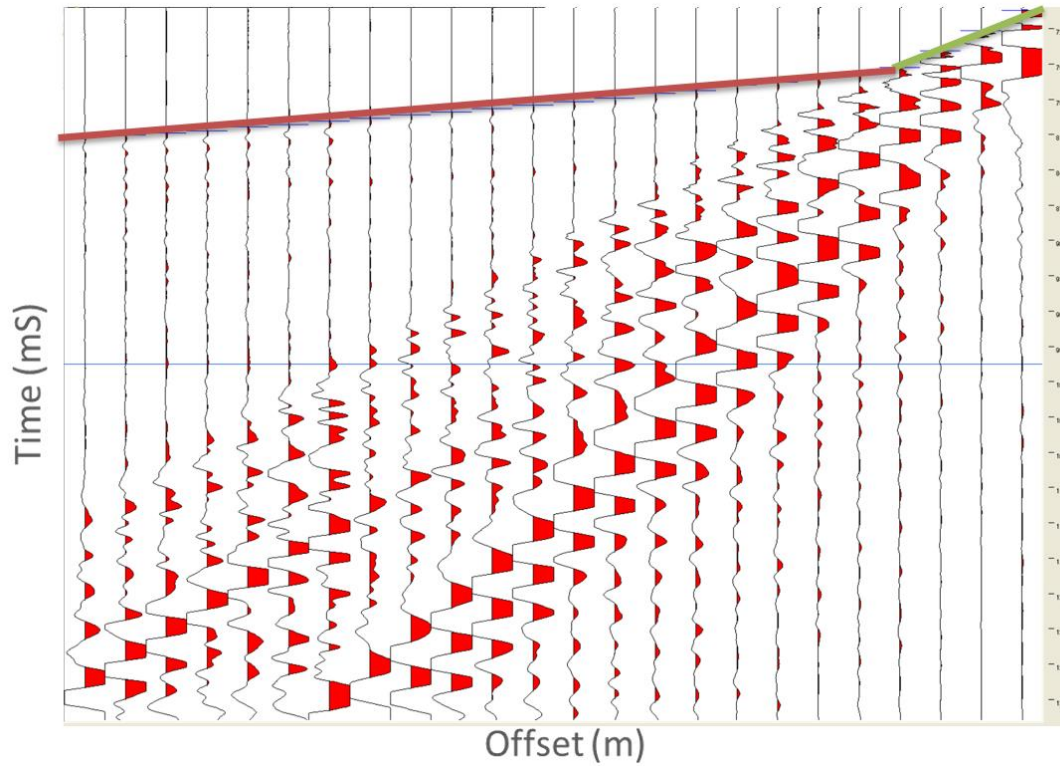


Figure 19 Seismic shot with source to the right of the line with indication of the direct (green) and refracted (red) first arrivals

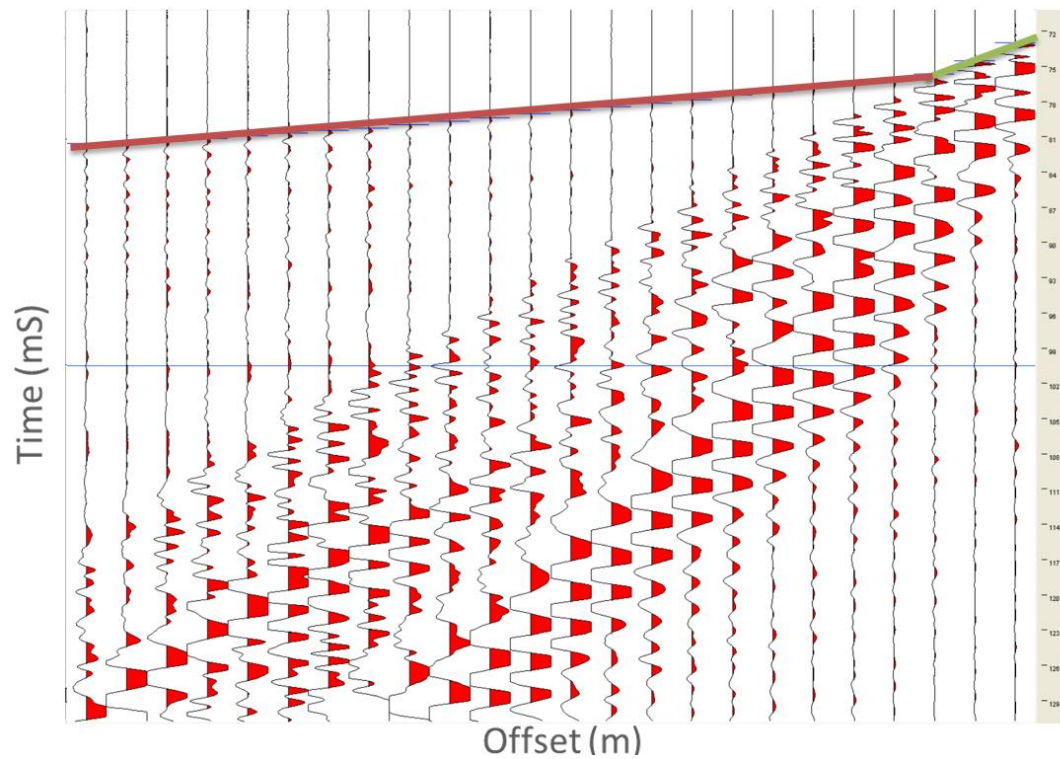


Figure 20 Seismic shot with source to the right of the line with indication of the direct (green) and refracted (red) first arrivals

For the case when both time and offset are independent variables, the following procedure will take place:

- (1) Data will be sorted in sets such that each set consists of four first arrival picks (T) corresponding to the same offset (X) from the four end shots.
- (2) Mean, standard deviation of first arrival picks and offsets will be calculated since both (T) and (X) have different readings.
- (3) Repeating all steps (3-13) from previous case study but taking into consideration the two changing factors: time and offset. The error propagation formula will be as follows:

$$\delta V = \sqrt{\left(\frac{\partial V}{\partial T} \delta T\right)^2 + \left(\frac{\partial V}{\partial X} \delta X\right)^2} \quad (8)$$

Where δV is the standard deviation of the velocity (V), δT , δX are the standard deviation of the time and offsets parameters respectively.

CHAPTER 4

RESULTS

4.1 Synthetic Data

The first arrival times were picked automatically and plotted against offset to estimate the velocity. Application of the methodology described in the previous chapter, results can be summarized in Table 1. Uncertainties in first arrival picks caused only 6.67% of relative uncertainty in velocity.

Table 1 Direct arrival picks (T) from synthetic data of end shot, offset (x), estimated velocity (V_e), True velocity (V_t) and error propagation in velocity calculations.

Station no	Times (s)	Offset (x)	Estimated Velocity (V_e)
1	0.0078152	0	280 m/s
2	0.613	0.2	True Velocity (V_t)
3	1.34	0.4	300 m/s
4	2.121	0.6	RU % of V
5	2.863	0.8	6.67
6	3.523	1	Final Form
			$V = 280 \pm 20$

4.2 Case Study I

For each of the six surveys, the first arrival times on all five shots were picked manually and plotted against offset to estimate the velocity of the unsaturated sand layer. The estimated velocity of the unsaturated sand was in the range of 200-400 m/s. I used the method described in the previous chapter to calculate error propagation after finding derivative for velocity formula and calculating the mean and standard deviation for first arrival picks. After that, I use the mean velocity and error propagation to estimate the best velocity and error propagation values (Tables 2 - 5). I only use the nearest 5 stations because the direct-wave arrival is present only on them as first arrival and possible to pick. The maximum relative uncertainty percentage of velocity encountered is around 20% corresponding to shot location of 0.5 m to the right of receiver line. This can be attributed to the increasing amount of noise in this shot.

Table 2 First arrival picks (T) corresponding to different stations from shot location at 2 m to the left of receiver line, mean ($\bar{T}$), standard deviation of first arrival picks (δT), velocity (V), and error propagation in direct-wave velocity calculations.

Station Number					
	1 st station	2 nd station	3 rd station	4 th station	5 th station
Shot no	First arrival picks of different stations T (ms)				
1	8	9	10	10	11
2	7	8	9	9.5	10
3	7	8	9	9	10
4	7	7.5	8	8.5	9
5	7	8	9	9.5	10
6	7	8	9	10	10.5
Mean $\bar{T}$ (ms)					
	7.167	8.083	9.00	9.417	10.08
δT (ms)					
	0.408	0.491	0.632	0.584	0.664
Relative uncertainty % of T					
	5.696	6.081	7.027	6.207	6.590
V (m/s)					
	279.1	272.1	266.7	276.1	277.7
δV (m/s)					
	15.89	16.55	18.74	17.13	18.30
Relative uncertainty % of V					
	5.696	6.081	7.027	6.207	6.590
Avg(V)	274.3		Avg(δV)		17.32
Final form	V=274 $\pm$ 17		RU%		6.3%

Table 3 First arrival picks (T) corresponding to different station from shot location at 2 m to the right of receiver line, mean ($\bar{T}$), standard deviation of first arrival picks (δT), velocity, and error propagation in direct-wave velocity calculations.

Station Number					
	1 st station	2 nd station	3 rd station	4 th station	5 th station
Shot no	First arrival picks of different stations T(ms)				
1	7	8	8	9	10
2	7	8	9	9.5	10
3	7	8	9	9	10
4	7	7.5	8	8.5	9
5	7	8	9	9	10
6	7	8	9	10	10.5
Mean $\bar{T}$ (ms)					
	7	7.917	8.667	9.167	9.917
δT (ms)					
	0	0.204	0.516	0.516	0.492
Relative uncertainty % of T					
	0	2.578	5.958	5.633	4.957
V(m/s)					
	285.7	277.9	276.9	283.6	282.4
δV (m/s)					
	0	7.165	16.50	15.98	13.99
Relative uncertainty % of V					
	0	2.578	5.958	5.633	4.957
Avg(V)	281.3		Avg(δV)		10.72
Final form	V=281 $\pm$ 10		RU%		3.8%

Table 4 First arrival picks (T) corresponding to different station from shot location at 0.5 m to the left of receiver line, mean ($\bar{T}$), standard deviation of first arrival picks (δT), velocity, and error propagation in direct-wave velocity calculations.

Station Number					
	1 st station	2 nd station	3 rd station	4 th station	5 th station
Shot no	First arrival picks of different stations T(ms)				
1	2	3	4	5	6
2	2	3	4	5	6
3	2	3	4	5	6
4	2	3	4	5	6
5	2	3	4	5	6
6	2	3	4	5	6
Mean $\bar{T}$ (ms)					
	2	3	4	5	6
δT (ms)					
	0.0	0.0	0.0	0.0	0.0
Relative uncertainty % of T					
	0.0	0.0	0.0	0.0	0.0
V(m/s)					
	250	233.3	225	220	216.7
δV (m/s)					
	0.0	0.0	0.0	0.0	0.0
Relative uncertainty % of V					
	0.0	0.0	0.0	0.0	0.0
Avg(V)	229			Avg(δV)	0.0
Final Form	V=229 $\pm$ 0.0		RU%		0.0%

Table 5 First arrival picks (T) corresponding to different station from shot location at 0.5 m to the right of receiver line, mean ($\bar{T}$), standard deviation of first arrival picks (δT), velocity, and error propagation in direct-wave velocity calculations.

Station Number					
	1 st station	2 nd station	3 rd station	4 th station	5 th station
Shot no	First arrival picks of different stations T(ms)				
1	2	3	4	5	6
2	1	2	3	4	5
3	1	2	3	4	5
4	2	3	4	5	6
5	2	3	4	5	6
6	1	2	4	5	6
Mean $\bar{T}$ (ms)					
	1.5	2.5	3.667	4.667	5.667
δT (ms)					
	0.5477	0.5477	0.5164	0.5164	0.5164
Relative uncertainty % of T					
	36.51	21.91	14.08	11.066	9.113
V(m/s)					
	333.3	280	245.5	235.7	229.4
δV (m/s)					
	121.7	61.34	34.56	26.08	20.91
Relative uncertainty % of V					
	36.51	21.90	14.08	11.07	9.112
Avg(V)	264.8			Avg(δV)	52.92
Final form	V=264 $\pm$ 52			RU%	19.9%

4.3 Case Study II

For each survey, the first arrival times were picked manually and plotted against offset to estimate the velocity and the thickness of the unsaturated sand layers. The velocity of the unsaturated sand was in the range of 280-460 m/s. I used the method described in the previous chapter to calculate error propagation after finding partial derivatives for velocity formula with respect to time and offsets, and then calculating the mean and standard deviation for first arrival picks and offsets. After that, I used the mean velocity and error propagation to estimate the best velocity and error propagation values (Tables 6 - 7). I only use the nearest 2 stations because the direct-wave arrival is present on them as first arrival and possible to pick. The maximum relative uncertainty percentage of velocity encountered in the second case study is around 14% corresponding to shot location of 5 m to stations.

Table 6 First arrival picks (T) and offsets corresponding to different stations from shot location at 5 m away from different stations, mean, standard deviation of first arrival picks (δT) and offsets (δX), velocity, and error propagation in direct-wave velocity calculations.

Station no.	1 st station	2 nd station	23 rd station	24 th station
Shot no.	1	2	4	5
Offset X (m)	5.128	4.938	5.2	4.916
Mean $\bar{X}$ (m)	5.0455			
δX (m)	0.140241			
RU % of X	2.779			
Time T (ms)	14	16.5	14.5	18
Mean $\bar{T}$ (ms)	15.75			
δT (ms)	1.848423			
RU % of T	11.736			
V(m/s)	366.2857	299.2727	358.6207	273.1111
Avg(V) (m/s)	324.3226			
δV (m/s)	45.4143			
Velocity Uncertainty	39.1155			
RU % of V	14.00282			
Final Form	V=324±45			

Table 7 First arrival picks (T) and offsets corresponding to different stations from shot location at 10 m away from different stations, mean, standard deviation of first arrival picks (δT) and offsets (δX), velocity, and error propagation in direct-wave velocity calculations.

Station no.	1 st station	2 nd station	23 rd station	24 th station
Shot no.	1	2	4	5
Offset X (m)	10.066	9.893	10.072	10.116
Mean $\bar{X}$ (m)	10.03675			
δX (m)	0.098392			
RU % of X	0.9803			
Time T (ms)	28	31.5	27	34.5
Mean $\bar{T}$ (ms)	30.25			
δT (ms)	3.427827			
RU % of T	11.33166			
V(m/s)	359.5	314.0635	373.037	293.2174
Avg(V) (m/s)	334.9545			
δV (m/s)	37.55521			
Velocity Uncertainty	38.09767			
RU % of V	11.21203			
Final Form	V=334±37			

CHAPTER 5 CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

One of the objectives of error analysis is to quantify uncertainties and determine error propagation through different mathematical operations. Several methods have been shown to determine error propagation in different studies. In this study, I showed how to utilize general error propagation formulas which only require the possibility to differentiate the relationship of variables and calculate standard deviation, to estimate uncertainties in the dependent variable. I applied the method on synthetic and real seismic refraction data sets to quantify uncertainties in velocity arising from uncertainties in first arrival picks and offsets.

In the case that time is considered the only independent variable, then the relative uncertainty of time is roughly equal to the relative uncertainty of velocity, and this is expected by looking at the error propagation formula where only the uncertainty of first arrival picks on the right side of the equation will be contribute to the uncertainty of velocity on the left side. However, when both time and offsets are considered to be the dependent variables, their relative uncertainties will add up to form the uncertainty of velocities.

5.2 Recommendations

The following enhancements can be considered in future studies:

1. Expanding the application of this method to estimate uncertainties in velocities of refractions as well as reflections.
2. Applying this method to quantify uncertainties in depth determination.
3. Comparing the partial derivative approach, which is used in this study, with other methods.

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