ANALYSIS OF THE REPEATABILITY OF TIME-LAPSE 3D VSP MULTICOMPONENT SURVEYS, DELHI FIELD

by

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ABSTRACT

Delhi Field is a producing oil field located in northeastern Louisiana. In order to monitor the CO2 sweep efficiency, time-lapse 3D seismic data have been acquired in this area. Time-lapse studies are increasingly used to evaluate changes in the seismic response induced by the production of hydrocarbons or the injection of water, CO2 or steam into a reservoir.

A 4D seismic signal is generated by a combination of production and injection effects within the reservoir as well as non-repeatability effects. In order to get reliable results from time-lapse seismic methods, it is important to distinguish the production and injection effects from the non-repeatability effects in the 4D seismic signal. Repeatability of 4D land seismic data is affected by several factors. The most significant of them are: source and receiver geometry inaccuracies, differences in seismic sources signatures, variations in the immediate near surface and ambient non-repeatable noise.

In this project, two 3D multicomponent VSP surveys acquired in Delhi Field were used to quantify the relative contribution of each factor that can affect the repeatability in land seismic data. The factors analyzed in this study were: source and receiver geometry inaccuracies, variations in the immediate near surface and ambient non-repeatable noise. This study showed that all these factors had a significant impact on the repeatability of the successive multicomponent VSP surveys in Delhi Field.

This project also shows the advantages and disadvantages in the use of different repeatability metrics, normalized-root-mean-square (NRMS) difference and signal-to-distortion ratio (SDR) attribute, to evaluate the level of seismic repeatability between successive time-lapse seismic surveys. It is observed that NRMS difference is greatly influenced by time-shifts and that SDR attribute combined with the time-shift may give more distinct and representative repeatability information than the NRMS difference.
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CHAPTER 1
INTRODUCTION

Borehole seismic data are usually used to provide a velocity model and to accurately tie surface seismic data to subsurface formations. However, it is known that VSP surveys can also provide superior reflection images with higher frequency content and lower levels of background noise compared to images from surface seismic. The high frequency content of VSP data provides imaging detail with superior vertical and lateral resolution and the high signal-to-noise quality of the data yields images whose fidelity is sufficiently good that it is possible to identify time-lapse effects with confidence and monitor changes in the reservoir (O’Brien et al., 2004). In some cases, VSP can provide signal-to-noise ratios high enough to facilitate identification and mapping of pore-fluids and fluid contacts, and thereby facilitate 4D monitoring of target reservoirs (Kuzmiski et al., 2009).

The inherent 3D nature of the earth and the seismic method, plus a desire to obtain detailed reservoir information, has led to interest in acquiring some type of 3D data in boreholes (Gulati et al., 2004). The term 3D VSP is used to describe the measurement of seismic signals by borehole detectors using an areal distribution of surface shots. The repeatability of 3D surveys is much higher than the repeatability of 2D surveys acquired with the same parameters. The main reasons for this are the advantages in processing 3D data and illumination and visualization of the target (Pevzner et al., 2011). Therefore, 3D VSP is a valuable option for monitoring what is happening around a well, since it can produce superior reflection images with increased resolution compared to images from surface seismic and also provides data with higher repeatability compared with 2D VSP.

The time-lapse or 4D seismic method involves acquisition, processing, and interpretation of repeated seismic surveys over a producing hydrocarbon field. The ultimate goal in a time-lapse study is to produce a difference volume characteristic of changes occurring in the
reservoir between surveys (Altan et al., 2001). Time-lapse studies are increasingly used to evaluate changes in the seismic response induced by the production of hydrocarbons or the injection of water, CO$_2$ or steam into a reservoir. $V_p$, $V_s$, and the density of a reservoir change as a result of production or injection of CO$_2$, which appears in seismic data as amplitude and timing changes (Al Jabri, 2011). In another words, 4D seismic monitoring tries to identify where changes in pressure and saturation occur due to production and injection effects within a reservoir based on changes in the seismic response between successive surveys. Time-lapse seismic has a key role in enhanced hydrocarbon recovery from existing fields (Calvert, 2005).

A 4D seismic signal is generated by a combination of production and injection effects within the reservoir as well as non-repeatability effects due to, for instance, differences in acquisition, variations in the immediate near surface and ambient non-repeatable noise. In order to get reliable results from time-lapse seismic methods, it is important to distinguish between the production and injection effects from the non-repeatability effects in the 4D seismic signal. Increased repeatability is recognized as one major issue for improving the time-lapse seismic technology as a reservoir management tool (Landro, 1999). Subtle changes in the reservoir seismic response may be revealed by accurately repeating surveys. Therefore, an understanding of the factors influencing repeatability of land seisimics and evaluating limitations of the method are crucially important for its application in time-lapse projects.

Time-lapse seismic is routinely applied offshore. The use of time-lapse methodology onshore is relatively rare. It is widely accepted that the repeatability of land seismic data is relatively poor. However, it is less well understood that the factors causing non-repeatability are critically important for time-lapse land surveys (Al Jabri & Urosevic, 2010). A better understanding of these factors could help in the design of optimum land time-lapse surveys with improved levels of repeatability.

In this study, two 3-D VSP’s were acquired, one in June 2010 and the other in August 2011. In these VSP surveys, the borehole seismic records were captured while the surface seismic was being conducted. The main purpose of this work is to analyze how repeatable
are the data recorded on a permanently installed geophone array and how repeatability changes with inaccuracies in source positioning and also with differences in the near-surface conditions.

Most of the papers in the literature use NRMS difference as a standard metric to evaluate the level of seismic repeatability between successive time-lapse seismic surveys. Pevzner et al. (2011), Landro (1999), Houck (2007), Calvert (2005) are good examples of the use of NRMS difference to study repeatability. A new metric called signal-to-distortion attribute (SDR) was proposed by Cantillo (2011) and applied in deep offshore data. This research shows the value of the application of the SDR attribute in time-lapse land seismic studies.

1.1 Delhi Field

Delhi Field is located in northeastern Louisiana, 40 miles west of the Louisiana-Mississippi border and 35 miles from Monroe (Figure 1.1) and is noted as one of the major oil fields in the Gulf Coast (Bloomer, 1946). The field is 15 miles long by 2-2.5 miles wide covering an area of 6200 acres. The study area of the Reservoir Characterization Project (RCP) is concentrated in a four-square mile area (Figure 1.2).

The main reservoir, the Holt Bryant zone, is composed of the Lower Cretaceous Paluxy and Upper Cretaceous Tuscaloosa sandstones. It lies at depths between 3,000 and 3,500 feet and is approximately 12 miles long and 0.5 to 2 miles wide with 357 mmbo of original oil in place (OOIP).

Delhi Field was discovered in 1944. Due to a substantial drop of the reservoir pressure, a water injection program was initiated in 1953 to pressurize the reservoir and improve production (Figure 1.3). The water-flooding process was implemented from 1953 to 1987 and managed to recover 40% of OOIP. Denbury Resources started the CO$_2$ flooding program in November 2009. In the petroleum industry CO$_2$ is commonly injected into hydrocarbon reservoirs to enhance oil and gas recovery by increasing the pressure of the reservoirs and reducing the viscosity of the oil. They expected to recover an additional 17% of OOIP or approximately 61 million bbl of oil with this CO$_2$-EOR (enhanced oil recovery) operation
(Silvis, 2011).

Figure 1.1: Location of Delhi Field in northeastern part of Louisiana (Evolution Petroleum Corporation). Jackson Dome is the area from which the CO$_2$ is transported.

1.2 VSP data

In order to monitor the movement of the CO$_2$ plume several seismic surveys were acquired. A baseline P-wave survey was acquired in 2008. The first monitor P-wave survey was acquired in January 2010 using a combination of dynamite and mini-vibes. A second 3C survey was acquired on June 2010 and the third survey on August 2011, both using dynamite and shot by Tesla Conquest. 3D VSP surveys were acquired simultaneously with the acquisitions of the 3D surface seismic for all the monitors. The time-line describing the development of the field and acquired time-lapse seismic surveys is shown in Figure 1.3.
The VSP multicomponent datasets acquired in June 2010 (monitor 1) and August 2011 (monitor 2) will be used in this study. I will refer to these datasets as VSP 1 and VSP 2.

A permanent, 20-level, 3-component geophone cable was used for recording these two surveys. The twenty-level array of geophones was permanently installed within well 164-2. The permanent nature of the array was expected to improve repeatability and to reduce the cost of repeated monitoring surveys. It simplifies the issue of repeatability by eliminating variance in receiver position and orientation (Cornish et al., 2000).

These VSP surveys were recorded using GS-ONE, three-component geophones, manufactured by OYO GEOSPACE. A three-component geophone consists of two horizontal components and one vertical component. The first geophone is placed at the depth of 15 feet while the last geophone is at 950.75 feet. The receiver depth interval is 49.25 feet.
The borehole was filled with cement and the geophone array was cemented to surface. The borehole cementation substantially suppresses the generation of tube waves. Tube waves are created by the setting in motion of particles in the column of drilling mud that fills the well.

The two surveys used in this study were acquired using dynamite at a 30ft depth with 1.1 lbs charge size. The source interval was 165 ft, and the source line interval was 330 ft.

The number of shots for VSP1 was 1048 while the number of shots for VSP2 was 947. Most of the difference in shot numbers was due to additional infrastructure in the survey area at the time when the second survey (August 2011) was acquired (Lubis, 2012). An analysis was made in order to identify which shots occur just in one of the surveys. These shots were deleted because most of the repeatability analysis done in this project requires comparison in between corresponding shots for both surveys. Therefore, it is necessary to ensure that VSP1 and VSP2 has the same number of shots. The final number of shot points used for each survey was 932.

Figure 1.4 shows a map with the source locations for VSP1 (blue) overlaid with the source locations for VSP2 (red). The green triangle shows the location of the VSP well. An observation one can make from this figure is that most of the shot locations are really close to one another, and some other shot locations present differences in positioning from one survey to the other. An analysis of the difference in the source locations for both surveys and how it influence the repeatability will be shown in chapter 4.

1.3 Non-repeatability causes

Repeatability of 4D land seismic data is affected by several factors. The most significant of them are: source and receiver geometry inaccuracies, differences in seismic sources signatures, variations in the immediate near surface and ambient non-repeatable noise (Pevzner et al. (2011), Jervis et al. (2012), Al Jabri (2011)). These factors are shown in Figure 1.5.

In order to accurately detect small changes due to production and injection effects within the reservoir, the sources and receivers of time-lapse multicomponent VSP surveys must be
Figure 1.4: Source locations for VSP1 (blue) overlaid with the source locations for VSP2 (red). The green triangle shows the position of the VSP well.

located exactly at the same positions. However, in practice, the source locations and the receiver orientations, if the array is not permanent, can vary from one survey to another survey. Repeatability of the acquisition geometry is very important for time-lapse studies, in order to resolve only time-lapse effects (Oghenekohwo & Herrmann, 2013). By analyzing the shotpoints for both surveys in the map (Figure 1.4), it is observed that some shot locations are really close to one another and other shot locations present differences in positioning from one survey to the other. This geometry provides data to study how repeatability can be improved by increasing the positioning accuracy of the source locations. This study is shown in chapter 4.

Since the two VSP surveys used permanent borehole arrays, the receiver geometry will not influence the repeatability of these data. The permanent array can provide data of sufficient quality to be applied to the task of time-lapse reservoir monitoring (Cornish et al., 2000).
In chapter 4, some errors in receiver orientation will be simulated in order to investigate how repeatability is affected by errors that may be generated when the borehole array is not permanent.

Propagation of the seismic waves through the near-surface layer may severely degrade seismic data quality, which is of particular importance in the interpretation of multicomponent seismic data (Zeng & MacBeth, 1996). Because of this, changes in near-surface conditions could be very important for repeatability of time-lapse surveys. In this case, the near-surface conditions varied from survey-to-survey, due to changes in soil saturation. When the first survey was acquired, the soil was wet, while when the second survey was acquired the soil was dry. The focus of this near-surface study will be on factors that can influence the repeatability of the land seismic data. It is expected that the attenuation and also the velocity of seismic waves in both surveys should be different due to these changes in the near-surface conditions. Time-shift maps, and amplitude spectral ratio maps will be estimated for both surveys to quantify the relative contribution of this factor into the overall non-repeatability of 4D surveys.

The VSP method of seismic data acquisition is a well-known technology whose advantage over surface data with regard to signal-to-noise and resolution near the borehole is generally accepted. It is expected to have less ambient noise affecting VSP data because the geophones are buried. Therefore, the ambient noise present in VSP data usually comes from the source. In this project, the ambient noise will be analyzed using signal-to-noise ratio attribute sections.

Andorsen & Landro (2000) found that there is a strong correlation between variations in the source signatures and lack of repeatability in the VSP data. The lack of repeatability of source signature is largely caused by the near surface being excited beyond its elastic limits, resulting in permanent, inelastic changes. These permanent changes may be credited to changes in absorption, which causes a constant phase delay, and/or changes in cohesive structure, which causes a constant time delay (Aritman, 2001). An analysis of how repeata-
bility can be affected by differences in source signatures is not done in this project and is left as a recommendation for future work.

Figure 1.5: Factors that can cause non-repeatability in land seismic data.

1.4 Motivation and objectives

4D technology is making dramatic advances in our ability to manage fields and increase their value. The sensitivity of 4D monitoring depends upon data repeatability. The more closely data are repeated, the smaller the reservoir changes we can diagnose. The smaller the production-related changes we can diagnose and recognize as deviations from model prediction, the earlier we have warning that our predictive model is in error and the earlier we can take corrective action and have greater impact upon field management (Calvert, 2005). Therefore, by increasing repeatability it is possible to improve the time-lapse seismic technology as a reservoir management tool.

The objective of this onshore repeatability study is to quantify the relative contribution of each factor that can affect the repeatability in a land seismic data. The factors analyzed in this study are: source and receiver geometry inaccuracies, variations in the immediate near surface and ambient non-repeatable noise. Understanding the factors that affect repeatability in time-lapse seismic projects can give insight into which factors are dominant and how they
can be mitigated (Jervis et al., 2012). 4D seismic data with higher repeatability can be more sensitive to small changes within the reservoir related to production and injection effects that can make a significant impact by enabling better field production diagnoses and by improving the field performance with less risk. Another goal of this project is to understand the advantages and disadvantages in the use of different repeatability metrics, normalized-root-mean-square (NRMS) difference and signal-to-distortion ratio (SDR) attribute, to evaluate the level of seismic repeatability between successive time-lapse seismic surveys.

1.5 Software used

To achieve the goal of this project, firstly it was necessary to do some processing in the data that will be explained in chapter 2. This 3D VSP processing was performed in Landmarks commercial software, Promax 3D. To calculate the repeatability metrics and the signal-to-noise ratio attribute and to plot all the maps shown in this thesis, Madagascar, Scilab and Python languages were used. Programs were also made to calculate variograms that are shown in chapter 4 using BrOffice Calc.
CHAPTER 2
SEISMIC PROCESSING STEPS AND PRELIMINARY REPEATABILITY ANALYSIS

To achieve the goal of this project, firstly it was necessary to process the data. Since the objective of this project is related to understanding factors that can affect repeatability in land seismic data, it was not necessary to do all the processing steps usually applied for imaging purposes. Both 3D VSPs were processed using the same sequences and parameters to exclude the effect of different processing steps in the repeatability analysis.

After geometry assignment, the tool was oriented to conform every receiver to one global coordinate system. The receivers were additionally inclined toward the incident downgoing wave in order to constrain the energy of downgoing compressional waves on one component and shear waves on a plane (Michaud, 2001). Cross-correlation was used to indicate which receivers were too noisy and should not be taken into account in the repeatability analysis.

All the processing steps shown in this chapter were performed with the ProMax (Landmark, Halliburton) processing software system.

In this chapter, a preliminary analysis of the repeatability in the VSP data is conducted in both time and frequency domain. Seismic repeatability is critically important in order to determine the level of confidence in the interpretation of any seismic changes related to production or injection effects. On land, non-repeatability effects are produced by differences in the acquisition geometry, variations in the near surface conditions, differences in the source signature and ambient noise. The analysis conducted in this chapter is made in a general way. Repeatability metrics are not used in order to quantify the non-repeatability in the raw data and there is no attempt in correlate any of the non-repeatable events found with the factors that can cause non-repeatability in land seismic data. The analysis including the repeatability metrics are shown in chapter 3 and the analysis including correlation with these factors are made in chapters 4 and 5.
2.1 Geometry assignment and first break picking

In this processing step, firstly some tables in the database were filled with survey information as positions of the sources and the receivers, charge and depth of the sources and grid informations. Then, this information was loaded in the header of the traces.

First breaks were also picked in this step. First break is the time of the first arrival or the time when the direct P-wave hits the geophone. The quality control of the 3D VSP geometry involves observing first break picks. First break picks were also used in the processing step explained below.

2.2 Tool orientation

3D multicomponent VSP data are recorded with receivers made of three mutually orthogonal geophones. One geophone is oriented toward the vertical direction, whereas the two others are free to orient toward any arbitrary direction in the horizontal plane (Michaud, 2001). The vertical component direction is downward and the horizontal components azimuths are randomly oriented. Because of this, from one receiver level to another, the two horizontal components can be oriented differently.

It is necessary to remove the effect of the different receiver orientations in order to compare data recorded at different levels or at different tool positions. This correction involves rotating the data to a global coordinate system, common for all receivers (Michaud, 2001). The chosen coordinate system is radial relative to the shot point. The orientation process is performed using the direct P-wave polarization plane method. This method assumes that P-wave energy is linearly polarized in the radial direction given by source and receiver coordinates.

The VSP data are rotated in the horizontal plane to orient one horizontal component with the source-receiver direction, often referred to as the horizontal radial component, and the other component orthogonal is referred to as the transverse component (Kuzmiski et al., 2009). The receiver is oriented by rotating the horizontal components about the vertical axis,
until the energy of the first compressional arrival is maximized on one horizontal component. This processing step is made based on hodogram analysis. A hodogram represents particle motion in 2-D (Figure 2.2). Hodogram analysis (Hinds et al., 1996) performed on the first break wavelets of the two horizontal datasets (from the same source location) is used to polarize the x and y data onto two principal axes that are normal (transverse) and tangential (radial) to the plane defined by the source and the well. The hodogram usually resembles an ellipse pointing in the direction of the azimuth of the downgoing wave (Figure 2.2). The hodogram method polarizes the horizontal axis data using the downgoing P-wave energy in the first break wavelet. A time window around the first break of 16 ms was selected, and the data from the two horizontal channels were plotted on an orthogonal axis. The angle found in the hodogram analysis is used to calculate the real orientation of the horizontal components and also to calculate the radial and transverse component traces.

Just a few shots around the wellbore with offsets less than 1000 ft were used in order to avoid the influence of lateral refraction in the estimation of the real orientation of the horizontal components. The angle for the real orientation of the horizontal components is given by the subtraction of the known source azimuth by the maximum signal polarization direction found using the hodogram analysis. The computed angle of actual orientation for each geophone is given by the average of the angles found for all these few shots (Lubis, 2012). The estimated angle of the tool orientation is then applied to the corresponding receiver on both horizontal components.

The calculus of the orientation angles is made for VSP 1. However, since the geophones are permanently installed the orientation of the horizontal components are the same for VSP 1 and for VSP 2. Therefore, the same orientation angles found for VSP 1 are applied for VSP 2.

After tool orientation, one of the horizontal components is rotated to the source-receiver direction or to the direction of maximum signal polarization. This rotation produces three output wavefields: vertical, transverse and radial. In the vertical component, the particle
motion is confined to the plane of the source-receiver pair and in the direction of propagation. In the radial component, the particle motion is transverse to the direction of wave propagation and in the plane of the source-receiver pair. In the transverse component, the particle motion is orthogonal to the radial component. The P-wave source was expected to produce a strong vertical component and a strongly SV-wave oriented to the radial component. Energy on the transverse component was expected to be minimized (Cornish et al., 2000). Therefore, the energy created by the compressional wave source is mainly recorded by vertical and radial components. The transverse component contains polarized SH waves as well as out-of-plane reflections and the vertical and radial components contain combined downgoing and upgoing P and SV waves.

Figure 2.3 shows the same shot shown on Figure 2.1 after tool orientation. This record from left to the right corresponds respectively to: vertical, transverse and radial components. A first observation one can make from this figure is that there is little energy in the transverse component. This energy can be related to anisotropy, heterogeneities or random noise. As expected, the vertical and the radial components contain the main energy created by the explosive source.

2.3 Rotation to the maximum P-wave

The goal of this research is to understand factors that can affect repeatability in land seismic data. Because of this, in some of the repeatability analyses only the direct downgoing P wave will be used since it is the least contaminated from other waves and has higher signal-to-noise ratio. Moreover, the downgoing waveform in VSP data provides reliable information about the evolution and attenuation of the seismic wavelet.

In the acquisition of these surveys, explosive sources and three component geophones were used in order to emphasize P- and converted S-waves. As stated by Yang et al. (2007), when the media around the shot point is isotropic, and the the vibrations generated by the source are the same in various directions, then pure P-waves are produced. In practice, it is impossible for the dynamite and surrounding media to satisfy all of the conditions and both
P- and S-waves are produced. The intensity of the generated downgoing S-waves depends on the characteristics of the dynamite and surrounding media.

Previous studies show that this kind of P-wave source generates relatively strong pure P-waves and weaker pure S-waves. Downgoing S-waves observed at zero offset can be divided into two categories: pure S-waves produced near the source and downgoing converted S-waves produced when P-waves are transmitted at a high Poisson’s ratio interface. Yang et al. (2007) states that the main frequency of pure S-wave is usually lower than the pure P-waves while the main frequency of a downgoing converted wave is close to that of a P-wave.

The first rotation was performed on the horizontal plane to orient one horizontal component with the source-receiver direction (maximum energy) and the other horizontal component orthogonal to this (minimum energy). In order to isolate the downgoing P-wave events in one component, and the downgoing S-wave events in another component, another rotation
Figure 2.2: Hodogram analysis. The data in a window around the first break from the two horizontal channels are plotted on an orthogonal axis. The hodogram usually resembles an ellipse pointing in the direction of the azimuth of the downgoing wave.

This processing step is also based on hodogram analysis. In this case, the rotation angles used for the polarization are found using a hodogram analysis of the vertical and radial components input data.

This rotation produces three output wavefields: P, SV and SH. P- and SV- waves in an isotropic medium are aligned toward the source; one component contains all the downgoing P wave energy and the other component contains the downgoing SV- energy. The up-going P and SV wave-fields exist mixed on both of these components (Kuzmiski et al., 2009). Figure 2.4 shows the record for the same shot shown in Figure 2.1 and Figure 2.3 after the second rotation. As can be seen in this figure, downgoing P-wave events are isolated in the component on the left, that from now on will be called component 1, and the downgoing
Figure 2.3: Data after tool orientation. This record from left to right corresponds respectively to: vertical, transverse and radial components. The transverse component contains polarized SH-energy as well as out of plane reflections and the vertical and radial components contain combined P- and SV- energy.

SV-wave events are present mainly in the component on the right that from now on will be called component 2. After a visual inspection of some shots, it was possible to see that the downgoing transmitted P and S-waves begin to refract at the shallower receivers as offset increases. In all the following analyses just the components 1 and 2 are used. The transverse component is not used in the studies presented in this thesis.

Figure 2.5 shows the data after this second rotation, highlighting that the P-wave downgoing energy is constrained in one component (left) and the downgoing S-wave energy is constrained in another component (right). The frequency of the downgoing S-waves is obviously lower than that of the downgoing P-waves. Since downgoing converted S-waves produced when P-waves are transmitted at a high Poisson’s ratio interface should have primary frequency similar to the transmitted P-wave, the downgoing S-wave shown in Figure 2.4 and Figure 2.5 should be pure S-waves produced at the source.
Figure 2.4: Data after second rotation. The downgoing P-wave was maximized in one component. The record in the left shows the component in which the downgoing P-wave was maximized, the record in the middle contains polarized SH-energy and the record in the right contains maximized downgoing S-wave.

Figure 2.5: Data after second rotation. The yellow and blue circles in the figures are highlighting the downgoing P-wave and the downgoing S-wave, respectively.
2.4 First break picking

After the second rotation, the first break was picked in the data, in the component that contained the downgoing P-wave. These picks were made just for some receivers (4, 6, 12 and 18) and all shots. These picks were made visually, without using any automatic process. Later, these first break picks were used to compute the time-shift maps for some receivers, as explained below. Figure 2.6 shows two shots with the first break picked.

![First break pick](image)

Figure 2.6: First break pick. All the picks were made in a visual way without using any automatic process.

2.5 Cross correlation

The cross-correlation between the traces of survey 1 and survey 2, for each shot, was used to analyze the receivers that presented good repeatability. In another words, cross-correlation was used to help choose some receivers that had a low signal to noise ratio and because of this were not included in the repeatability analysis.

Cross-correlation analysis was made for all the shots. Figure 2.7 shows the result of the cross-correlation for one shot. The result showed that the three shallower receivers have a poor correlation for almost all the shots. Therefore, these three shallow receivers will not be taken into account in the following repeatability analysis.
Figure 2.7: Cross-correlation between corresponding traces of a shot from VSP 1 and of a shot from VSP 2. This cross-correlation shows that the three shallower receivers were noisy and should not be taken into account in the following analysis.

2.6 Preliminary repeatability analysis in time-domain

To better understand the behavior of these data related to repeatability, firstly I plotted the near-offset shot from survey 1, with the first near-offset shot from survey 2 and the difference between them (Figure 2.8). This difference was computed as a direct subtraction (sample by sample) of the monitor 1 shot gather and the monitor 2 shot gather.

As can be seen in Figure 2.8, the difference between these two shots is remarkable which implies that there is significant non-repeatability between the raw data from both surveys that may be caused by some of the factors that can influence repeatability in land seismic data, such as source positioning errors, differences in seismic source signatures, near surface conditions and ambient noise.

There are several techniques available to enhance the repeatability between successive surveys in time-lapse projects. One of them is related to correct time-shifts, bandwidth and phase using a cross-equalization process. A commonly used method for equalizing two seismic surveys is composed of the following steps (Cheng et al., 2009):

- (1) First break time alignment: align the first break of the repeat survey with the baseline.
Figure 2.8: Near-offset shot from survey 1 on the left, from survey 2 in the middle and the difference between them on the right. This shows a remarkable difference between these two shots that may be caused by factors shown in Figure 1.5

- (2) Match-filtering: The spectrum of the repeat survey is matched to the baseline survey inside a specific window by the use of the Wiener-Levinsion algorithm.

- (3) Gain equalization: A global gain equalization is then applied to both data sets.

These processes used to enhance the repeatability between successive surveys are not applied to the data in this thesis because the main purpose of this research is related to evaluate the level of seismic repeatability in the raw data at Delhi Field and to understand the factors that can cause non-repeatability in land seismic data.

After this first analysis, I plotted a seismogram with traces from survey 1 and survey 2 merged for the near offset shot. The objective of this plot is to show if there are phase and amplitude differences between traces from datasets from surveys 1 and 2. Figure 2.9 shows this seismogram.

By analyzing Figure 2.9, I noted a slight difference in the amplitude between traces from both surveys. A time-shift between traces from both surveys can also be observed. Differences in phase are not observed for this shot.
Time shifts are frequently observed between the surveys that comprise a time-lapse seismic dataset. The timing differences may be consistent, caused, for example, by different acquisition reference time definitions or by differences in the near surface conditions when the two surveys were acquired, or they may vary from line to line or shot to shot, perhaps as a result of variable source timing and geometry errors.

Time-shifts between the two surveys were estimated for some receivers and all the shots. The picks were made in the first arrivals in component 1 for both surveys. Then, these picks were subtracted from each other for corresponding traces from both surveys to compute the time-shift maps. Time-shift maps were generated for some receivers (4, 12 and 18). Figure 2.10 shows the time-shift map for receiver 12. The time-shift maps for receivers 4 and 18 are shown in chapter 5.

Figure 2.10 shows that the presence of time-shifts in the data between survey 1 and survey 2 are remarkable. The red color in the map corresponds to positive time shifts and the blue color in the map corresponds to negative time-shifts. Since these maps were generated as the values for the first break picks for survey 1 minus the values for the first break picks for
survey 2, positive time-shifts imply that the first break time for survey 1 is greater than the first break time for survey 2, and negative time-shifts imply the opposite.

As stated before, no process was used to equalize both data. The time-shift map shows punctual events that can probably be related to variable source timing between both surveys or to errors in the acquisition geometry. In general, time-shifts are positive in the north part of the map and negative or zero in the bottom part of the map. The discussions about the factors that can be causing these time-shifts and also the consistency of the time-shift maps for different receivers are made in chapters 4 and 5, respectively.

Figure 2.10: Time-shift map for receiver 12. These maps were generated as the values for the first break picks for survey 1 minus the values for the first break picks for survey 2. Positive time-shifts (red) imply that the first break time for survey 1 is greater than the first break time for survey 2, and negative time-shifts (blue) imply the opposite.

2.7 Preliminary repeatability analysis in frequency-domain

Another way to compare time-lapse seismic data is doing the analysis in the frequency domain. Non-repeatability of seismic data was investigated by computing and comparing the...
amplitude spectra of some shots from both surveys. This analysis was made for component 1 and for component 2. Figure 2.11 and Figure 2.12 are showing the frequency spectrum for survey 1 and for survey 2, for both components 1 and 2, respectively.

Figure 2.11: Frequency spectrum for component 1 of one shot from survey 1 on the top, and frequency spectrum for the same shot from survey 2, on the bottom. This figure shows that the frequency spectrum for the component 1 from survey 2 is more attenuated than the frequency spectrum for component 1 from survey 1.

A first observation one can make from these amplitude spectra plots is that the frequency content is different for both surveys, especially for component 1. The frequency spectrum for the shot from survey 2 is more attenuated than the frequency spectrum for the same shot from survey 1. For this shot, this difference is larger for the first component (Figure 2.11) than for the second component (Figure 2.12). This analysis was made for several shots,
Figure 2.12: Frequency spectrum for component 2 of one shot from survey 1 on the top, and frequency spectrum for the same shot from survey 2, on the bottom. This figure shows that the frequency spectrum for the component 2 from survey 2 is slightly more attenuated than the frequency spectrum for component 2 from survey 1.

and most of them showed the same behavior, the frequency content was less attenuated for survey 1 than for survey 2, specially for component 1.

Changes in the frequency spectrum may be related to some factors as, for example, ambient noise and with differences in the near-surface conditions. In this case, when the first survey was acquired the soil was wet, while when the second survey was acquired the soil was dry. According to Al Jabri (2011), it is reasonable to assume that the principal cause of non-repeatability issues in land seismic data is related to temporal variations of the near surface conditions. He showed that the change in water saturation of the near surface
can cause changes in velocity and attenuation and that the wet near surface can provide better seismic energy transmission and a broader signal compared to the dry near surface. Pevzner et al. (2011) also observed a much lower signal level during dry periods compared to wet periods. In this case, the same behaviour was observed for the amplitude spectra from both surveys, the data collected during the wet season (survey 1), had higher frequency content than the data collected during the dry season (survey 2) for most of the shots. This discussion continues in chapter 5.

It is known that upgoing P- and S-waves are presented in components 1 and 2 of the data. To better understand what causes component 1 to have a higher difference in the amplitude spectra compared to component 2, the frequency spectrum was plotted for component 1 for both surveys with a window around the downgoing P-waves, and for component 2 with a window around the downgoing S-waves. In this way, it is ensured that the main information in the frequency spectrum comes from P and from S-waves separately. Figure 2.13 and Figure 2.14 show the frequency spectrum for survey 1 and for survey 2 with the time-window applied, for both components 1 and 2, respectively.

By analyzing the frequency spectrum with the time-window applied around the downgoing P-waves for component 1, it is possible to observe that component 1 of the receivers is strongly dependent on water saturation. The frequency spectrum for survey 1 is remarkably less attenuated than the frequency spectrum for survey 2. On the other hand, the frequency spectrum with the time-window applied around the downgoing S-waves for component 2, shows a weak dependency on water saturation. It is expected since, as stated by Mavko et al. (2005), some laboratory and field data (albeit very sparse) indicate that the S-wave attenuation in a sediment sample weakly depends on water saturation.
Figure 2.13: Frequency spectrum for component 1 of one shot with a window around the downgoing P-wave from survey 1 on the top, and frequency spectrum for the same shot from survey 2, on the bottom. This figure shows that, for this shot, the amplitude spectrum for component 1 from survey 2 is remarkably more attenuated than the amplitude spectrum for component 1 from survey 1.
Figure 2.14: Frequency spectrum for component 2 of one shot with a window around the
downgoing S-wave from survey 1 on the top, and frequency spectrum for the same shot
from survey 2, on the bottom. This figure shows that, for this shot, the difference between
the amplitude spectrum for component 2 from survey 1 and the amplitude spectrum for
component 2 from survey 2 is remarkably less than the differences found for component 1.
CHAPTER 3
REPEATABILITY METRICS

One of the critical limitations encountered in time-lapse seismic projects is the degree of repeatability between successive surveys. Repeatability is a measure of the similarity of the seismic response between two seismic surveys excluding production-related effects (Li et al., 2004). The confidence level in interpretation of time-lapse events is directly related to the attained repeatability.

Kragh and Christie (Kragh & Christie, 2002) presented a paper on repeatability, normalized-root-mean-square (NRMS), and predictability (PRED) in 2001. Since then, NRMS and predictability have been the most widely used metrics for analyzing 4D noise in time-lapse studies. In papers related to 4D projects, NRMS is still the most used repeatability metric. In 2011 and 2012, Juan Cantillo (Cantillo (2011) and Cantillo (2012)) presented a different way to estimate time-lapse repeatability from the perspective of perturbation theory. He introduced the signal-to-distortion ratio (SDR) attribute as a reliable indicator of time-lapse repeatability.

In this project, to evaluate repeatability of the two surveys, two different metrics were computed: normalized-root-mean-square (NRMS) that measures the difference between two surveys, and the signal-to-distortion ratio (SDR) attribute that uses the cross-correlation between corresponding pairs of traces from different surveys. The advantages and disadvantages of these repeatability metrics are discussed in this chapter. Results of these repeatability metrics applied on component 1 and on component 2 of the Delhi multicomponent VSP data are also shown in this chapter.

3.1 NMRS difference

NRMS difference is one of the repeatability metrics that is most used in 4D projects to quantify the level of similarity between two traces. It is given by the RMS of the difference
between two corresponding traces from successive surveys divided by the average RMS of the inputs. It is expressed as a percentage. Normalized-root-mean-square difference is computed using the following equation (Kragh & Christie, 2002):

$$NRMS = 200 \frac{RMS(a - b)}{RMS(a) + RMS(b)} \%$$  \hspace{1cm} (3.1)

where \(a\) and \(b\) are the two input data, and the RMS operator is defined as:

$$RMS = \sqrt{\left( \sum x^2 \right)/N}$$  \hspace{1cm} (3.2)

where \(N\) is the number of samples in the window.

For NRMS, lower values generally correspond to better repeatability and higher values to less repeatability. In another words, when NRMS increases the repeatability decreases and vice versa. The values of NRMS are not intuitive and are not limited to the range 0-100%. As stated in Kragh & Christie (2002), for example, if both traces contain random noise, the NRMS value is 141% (\(\sqrt{2}\)). If both traces anti-correlate (i.e., 180° out of phase, or if one trace contains only zeros) the NRMS value is 200%, the theoretical maximum. If one trace is half the amplitude of the other, the NRMS value is 66.7%.

NRMS difference is affected by even small changes in the data. It is sensitive to overall phase, amplitude and time-shift differences. Because of this, the comparison of a trace with the same trace just with a static shift, can give the same NRMS value as the comparison of two traces with different shapes.

From Cantillo (2012), NRMS difference values in the range from 0% to 10% indicate excellent repeatability. Values in the range from 11% to 25% are considered good repeatability and in the range from 26% to 50% fair repeatability. From 51% to 200% the data are considered to have poor repeatability. These values are just approximations to give the reader insights about what to expect concerning repeatability for different NRMS values.

To evaluate the repeatability of survey 1 and survey 2, NRMS difference sections were computed for some shots. This calculation was made using a sliding window of 100ms. The NRMS sections were smoothed using a Gaussian filter. Figure 3.1 shows a NRMS section.
for component 1 of shot 1600547 and Figure 3.2 shows the seismograms for component 1 of this shot for survey 1 and for survey 2 side by side.

Figure 3.1: NRMS difference section for component 1 of shot 1600547. The lower values (blue) are related to higher repeatability, while the higher values (red) are related to lower repeatability.

Figure 3.2: Seismograms of component 1 of shot 1600547. On the left is the record for survey 1 and on the right is the record for survey 2.
The first observation one can make of the NRMS section shown in Figure 3.1, is that, in general, the repeatability is higher for the smaller times and is lower for the greater times. The low repeatability that occurs in the time window from 0 to 0.1s is related to the fact that until this time no signal arrived in the geophones and this region presents just random noise, as seen in Figure 3.2. Ambient noise occurring just before the first-breaks is related to the lowest signal-to-noise ratio and is not repeatable. The fact that the repeatability is higher for the smaller times and lower for the greater times should also be related to the S/N ratio. As the wave travels in the medium, the signal is attenuated and the signal to noise ratio decreases.

NRMS difference measures the relative difference between two seismic traces. Typical values for modern 4D surveys are 0.1 to 0.4, which represent an ability to reproduce seismic amplitudes to within 10-40% in the final stacked data (Miller & Helgerud, 2009). Houck (2007) states that recently, surveys with average NRMS difference of less than 20% have become common, and cases have been reported where NRMS values below 10% have been observed. Wu et al. (2011) showed that for their time-lapse 3D VSP project using a permanent array a repeatability of 20% was achieved within a range of 1500m around the VSP well. All these cases are related to data that are already processed and with cross-equalization techniques applied. In order to retain the inherent effect caused by each factor that affects repeatability on 4D land seismic data, no matching technique was applied to the data. Because of this, the values I found for the NRMS difference in this section are relatively high compared to the values in the literature that are usually calculated for the processed data with cross-equalization processes applied.

The next step was to generate a map of the NRMS values that provides spatial information about the repeatability. NRMS values were calculated for a window of 200ms around the direct downgoing wave. Only the direct downgoing wave was used to generate the maps of repeatability metrics because it is the least contaminated from other waves and has higher signal-to-noise ratio. Figure 3.3 shows this NRMS map.
Figure 3.3: NRMS difference map. Higher values of NRMS (red) indicate lower repeatability, while lower values of NRMS (blue) indicate higher repeatability.

Some observations can be made by analyzing the NRMS difference map (Figure 3.3). First of all, there are localized events that present low repeatability across the map. This is related to the fact that NRMS difference is affected by even small changes in the data. Some of these localized events will be explained in the following discussion and also in chapter 4. Another important observation is that there is a clear correlation between this NRMS map and the time shift map for receiver 12 shown in Figure 2.10. Figure 3.4 shows these two maps side by side highlighting some areas in which this correlation between both maps is remarkable.

Unsurprisingly, the comparison between the NRMS map and the time-shift map in Figure 3.4 shows that most of the anomalies present in the NRMS map are related to time-shifts between both data. The scale bar of the NRMS difference map is affected by the high values found for the NRMS values in the presence of large time-shifts. Because of this, it is hard to get information about the intrinsic shape similarity between corresponding traces.
Figure 3.4: NRMS map on the left and time-shift map for receiver 12 on the right. The black curves are highlighting regions in which the correlation between the NRMS map and the time-shift map are remarkable.

from both surveys in the NRMS difference map. In another words, the NRMS map does not provide clear information about amplitude and phase differences between traces because it is too sensitive to the time-shifts from both surveys. Some of the localized anomalies shown in Figure 3.3 are related to the punctual events on the time-shift map that are probably related to variable source timing between both surveys or to errors in the acquisition geometries. This last statement will be discussed in chapter 4.

To better understand the relation between NRMS difference values and time-shifts, a graph of the NRMS difference values versus time-shifts for receiver 12 was plotted. Figure 3.5 shows this graph. It is possible to see in this plot that there is a linear relation between the NRMS difference and the time-shift, in a way that when the time-shift increases the NRMS value also increases. The blue straight line in this plot corresponds to the linear best-curve fitting found using the linear least-squares methodology. The least-squares fitting is a mathematical procedure for finding the best-fitting curve to a given set of points by minimizing the sum of the squares of the offsets (“the residuals”) of the points from the curve (Weisstein, n.d.). These straight lines confirm that the NRMS differences increase with increasing time-shifts. The NRMS difference is a repeatability metric driven by time-
Figure 3.5: Plot of the NRMS difference values versus time-shifts for receiver 12. When the time-shift increases the NRMS difference also increases. The blue straight line corresponds to the linear best-curve fitting found using the linear least squares methodology. The NRMS difference increases with increasing time-shift.

The same analysis using the NRMS section was also made for some shots from component 2. Figure 3.6 shows the NRMS difference section for component 2 for the same shot shown in Figure 3.1. This section was calculated using the same sliding window used to calculate the NRMS section for component 1 shown in Figure 3.1. Figure 3.7 shows the seismograms for component 2 of this shot for survey 1 and for survey 2 side by side.

By analyzing Figure 3.4 some characteristics observed for the NRMS section for component 1 can also be observed for component 2. For example, the repeatability is low for component 2 in the very small times from 0 to 0.1s because, as stated before, until this time no signal arrived in the geophones and this region presents just random noise. Another observation is made for the component 1 section. In general, the repeatability is higher for the smaller times and is lower for the greater times. This happens because the signal to noise ratio is lower for the larger times. One interesting point that can be seen in this section is that the higher repeatability zone around 0.7s coincides with the region in the seismogram that the downgoing S-waves are present, as can be seen in Figure 3.7. More examples will be
Figure 3.6: NRMS difference section for the component 2 of shot 1600547. The lower values (blue) are related to higher repeatability, while the higher values (red) are related to lower repeatability.

Figure 3.7: Seismograms of component 2 of shot 1600546. On the left is the record for survey 1 and on the right is the record for survey 2.

shown in the end of this chapter in order to gain a better understanding of how repeatable the downgoing S-waves are.
3.2 Signal-to-distortion ratio (SDR) attribute

In the literature since 2001, NRMS and predictability have been the main metrics used for analyzing repeatability in time-lapse projects. Their values are not intuitive and their respective variations are still not fully understood. In order to improve the general understanding about time-lapse repeatability, Cantillo (2011) introduced an analytical formulation of the 4D problem from the perspective of perturbation theory called signal-to-distortion ratio SDR.

SDR is not affected by time-shifts between the data and is sensitive to amplitude and phase differences. Because of this, SDR is related to the intrinsic shape similarity between traces. Shape similarity is the one thing that intuitively ensures that acquisition and processing are on a good track regardless of the precise conditions under which the traces were observed (Cantillo, 2012).

SDR can be given as a function of the maximum reached by the normalized cross-correlation $x_{ab}$ function as follows (Cantillo, 2012):

$$SDR = \frac{\text{max}(x_{ab})^2}{1 - \text{max}(x_{ab})^2}$$ (3.3)

where a and b are the two input data, and x is the symbol for cross-correlation.

The values of the SDR can vary even 2 orders of magnitude within the same dataset. Because of this, it is usually given in decibels:

$$SDR_{dB} = 10\log_{10}(SDR)$$ (3.4)

It is possible to see in Cantillo (2012) that, SDR values in decibels in the range from 0 to 5 indicate poor repeatability. Values of SDR in the range from 5 to 12 are considered fair repeatability and from 12 to 20 good repeatability. Excellent repeatability will be reached for SDR values in the range from 20 to 30. These ranges of values are just approximations to give the reader insights about what to expect from the repeatability for different SDR values.
To evaluate the repeatability of survey 1 and survey 2, SDR attribute sections were computed for some shots. This calculation was made using the same sliding window used to calculate the NRMS sections of 100ms. The SDR sections were smoothed using a Gaussian filter. Figure 3.8 shows a SDR attribute section for component 1 of the same shot used to calculate the NRMS section in Figure 3.1.

Figure 3.8: SDR attribute section for component 1 of shot 1600547. The lower values (blue) are related to lower repeatability, while the higher values (red) are related to higher repeatability.

The same observations one could make of the NRMS section shown in Figure 3.1, are made for the SDR section shown in Figure 3.8. Firstly, repeatability is higher for the smaller times and is lower for the greater times. The low repeatability that occurs from 0 to 0.1s is related to the fact that until this time no signal arrived in the geophones and this region presents just random noise. Ambient noise occurring just before the first-breaks is related to the lowest signal-to-noise ratio and is not repeatable. The fact that the repeatability is higher for the smaller times and lower for the greater times should also be related to the
S/N ratio. The longer the wave travels in the medium, more the signal is attenuated and the signal-to-noise ratio decreases.

A comparison of the NRMS section (Figure 3.1) with the SDR section (Figure 3.8) shows that in general, these two sections have good correlations. For example, the highly repeatable events that appear in the NRMS section from 0.2 s to 0.9 s also appear in the SDR section. Figure 3.9 shows the NRMS section and the SDR section for another shot (1570546) side by side with a zoom in time to emphasize the similarities between these two sections.

As expected, the NRMS section and the SDR attribute section shown in Figure 3.6 are quite similar to each other. A great difference between these repeatability metrics is related to the fact that the SDR attribute is sensitive to amplitude and phase differences, while the NRMS difference is sensitive to amplitude and phase differences and also to time-shift. Thus, in the absence of time-shifts, both of them should present the same behavior.

The next step was to generate a map of the SDR attribute that provides spatial information about the repeatability. SDR attribute values were calculated for the same window of 100ms around the direct downgoing wave used to calculate the NRMS map. As before, only the direct downgoing wave was used to generate the maps of repeatability metrics because it is the least contaminated from other waves and has higher signal-to-noise ratio. Figure 3.10
Figure 3.10: SDR attribute map. Higher values of SDR (red) indicate higher repeatability, while lower values of SDR (blue) indicate lower repeatability.

As observed in the SDR attribute map (Figure 3.10), different from the NRMS difference map, the SDR attribute map is not driven by time-shift. Correlations between the time-shift map showed in Figure 5.1 and the SDR attribute map cannot be observed.

In order to retain the inherent effect caused by each factor that affects the repeatability on 4D land seismic data, no cross-equalization technique was applied to the data. Therefore, as expected, in some regions of the map there are relatively low values found for the SDR attribute, which indicates poor repeatability. The analysis including the causes for the low repeatability regions in the SDR map will be shown in chapter 5.

Figure 3.11 shows the SDR attribute map and the NRMS difference map side by side. To better illustrate the correlation between them, the SDR attribute map was plotted with inverted scale bar. Then, in both maps the blue color represents higher repeatability and the red color represents lower repeatability.
Figure 3.11: SDR attribute map on the left and NRMS difference map on the right. The SDR attribute map was generated with the scale bar inverted to match with the NRMS difference map scale bar. Now, in both maps blue color represents higher repeatability and red colors represents lower repeatability. The black curves are highlighting regions in which the SDR attribute map and the NRMS difference map correlate with each other. Both of them indicate high repeatability in these regions.

It is possible to see in Figure 3.11 that, since the NRMS difference map is driven by time-shift and the SDR attribute map is not sensitive to time shift, in the regions in which time-shifts are higher (highlighted in Figure 3.4), these maps do not correlate with each other. In this figure the black curves are highlighting some regions in which the SDR attribute map and the NRMS difference map correlate with each other. In these regions, both of the maps show higher repeatability. In regions in which the repeatability is intermediary to poor, it is harder to see correlation between these maps because the scale bar of the NRMS map is affected by the higher values found for the NRMS values in the presence of large time-shifts.

Repeatability is driven by a combination of time-shift, additive noise, amplitude and phase differences. Additive noise includes ambient noise and source-generated noise that does not originate at the target reflector (Houck, 2007). Both repeatability metrics, NRMS difference and SDR attribute, are affected by additive noise. Besides this, NRMS difference is also influenced by the other parameters that affect repeatability, time-shift and amplitude and phase differences. Because of this, depending on the intensity of the time-shifts, it can
be harder to interpret NRMS values as a representative repeatability information since it does not distinguish between information about time-shift and information about amplitude and phase differences. On the other hand, the SDR attribute takes into account just the amplitude and phase differences between traces from successive surveys. The time-shift parameter can be estimated as shown before by subtracting the first-arrival times from both surveys or by using the time of the maximum cross-correlation (Figure 3.12). The time-shift map estimated by using the time of the maximum cross-correlation just gives the intensity of the time-shifts and not if they are positive or negative. The comparison between the map for time-shifts shown in Figure 3.12 and the NRMS difference map shown in Figure 3.3 demonstrates that both maps are quite similar which reflects the impact on the NRMS value of the time-shifts. On the other hand, SDR attribute maps can be interpreted as differences in amplitude and phase between successive surveys. Therefore, the SDR attribute combined with the time-shift maps might give more distinct and representative repeatability information than the NRMS difference.

The same analysis using the SDR section was also made for some shots from component 2. Figure 3.13 shows the SDR attribute section for component 2 for the same shot shown in Figure 3.8. This section was calculated using the same sliding window used to calculate the SDR section for component 1 shown in Figure 3.8.

Again, the same observations made for the NRMS difference section shown in Figure 3.6 can be made for the SDR attribute section in Figure 3.13. For the same reason stated before, the very shallow zones from 0 to 0.1s present low repeatability and in general the repeatability is lower for the larger times and is higher for the smaller times. The same event that occurs around 0.7s with high repeatability that could be seen in the NRMS difference section, can also be seen in the SDR attribute section. As stated before, this event corresponds to the region where the downgoing S-waves are presented (Figure 3.7).

Figure 3.13 shows the NRMS difference section and the SDR attribute section for component 2 of the near-offset shot (1570546) side by side zoomed from 0 to 1.5s. The presence
of an event with high repeatability around 0.6s is evident in both sections. Figure 3.15 shows the seismograms of component 2 of the near-offset shot also zoomed in 1.5s. The comparison of this seismogram with the repeatability metrics section in Figure 3.14 for this same shot shows that the event with high repeatability in both sections around 0.6s coincides with the region in which the direct downgoing S-wave is present.

The downgoing S-wave could not be observed for all the shots. This happened in most of the cases because the S-wave is slower than the P-wave, and for larger offsets it reaches the geophones probably in a time higher than the recording time. However, when the downgoing S-wave was present in the data, it showed in most of the cases, a high repetitive behavior on the same order of magnitude as the downgoing P-wave. Even when the offset is higher and the S-wave appears as a turning wave in the seismogram, it still shows a repeatable behavior. To better illustrate this fact that the downgoing S-wave is a repeatable event in

Figure 3.12: Time-shift map estimated using the time of the maximum cross-correlation between traces from both surveys. This map has a good correlation with the time-shift map picked manually as the difference of the first-arrival time for both surveys.
Figure 3.13: SDR attribute section for component 2 of shot 1600547. The lower values (blue) are related to lower repeatability, while the higher values (red) are related to higher repeatability.

Figure 3.14: NRMS section on the left and SDR attribute section on the right for component 2 of the near offset shot (1570546) zoomed in time to emphasize the similarities between these two sections. The event that appears around 0.6s coincides with the region in which the downgoing S-waves are present.
the data, Figure 3.16, Figure 3.17, Figure 3.18, Figure 3.19, Figure 3.20, Figure 3.21 and Figure 3.22 show component 2 for some different shots from both surveys and the respective repeatability metrics sections. It is possible to see in this figures that for almost all these shots, the downgoing S-wave appears as a repeatable event in the repeatability metrics sections. As stated by Yang et al. (2007), the intensity of the generated downgoing S-waves by explosive sources depends in the characteristics of the dynamite and surrounding media. Apparently, even though these characteristics may change from one acquisition to the other, it does no affect as much the shape of the downgoing S-wave records and it appears as a repeatable event in the seismic data.

The downgoing S-wave from an explosive sources is not controllable. The fact that the downgoing S-wave generated by explosive sources when present in the data, appears to be a repeatable event, implies that this kind of wave can be used in estimations of time-lapse properties as, for example, S-wave velocity and S-wave quality factors. It is difficult to observe pure S-waves in multicomponent surface seismic records because in surface observations S-waves pass through the low-velocity layer when they are transmitted upward to the surface geophones. Since the low-velocity layer strongly absorbs and attenuates S-waves, the S-wave energy will be extremely weak when the arrivals reach the surface (Yang
et al., 2007). Studies need to be done in order to show what kind of new information the downgoing S-waves generated by explosive source and recorded in a multicomponent VSP survey can bring in a time-lapse project, but it is not going to be shown in this thesis and will be left as a recommendation for future work.

Figure 3.16: The repeatability metrics sections for component 2 of the shot 1570547 in the top and the seismograms from survey 1 (left) and from survey 2 (right) for this shot in the bottom. In the top left is the NRMS difference section and in the right is the SDR attribute section. The downgoing S-waves that appear around 0.6s in the seismograms show a repeatable behavior in the repeatability metrics sections.
Figure 3.17: The repeatability metrics sections for component 2 of the shot 1570552 in the top and the seismograms from survey 1 (left) and from survey 2 (right) for this shot in the bottom. In the top left is the NRMS difference section and in the right is the SDR attribute section. The downgoing S-waves that appear around 0.7s in the seismograms show a repeatable behavior in the repeatability metrics sections.
Figure 3.18: The repeatability metrics sections for component 2 of the shot 1600525 in the top and the seismograms from survey 1 (left) and from survey 2 (right) for this shot in the bottom. In the top left is the NRMS difference section and in the right is the SDR attribute section. The turning S-waves that appear around 2.0s and 2.8s in the seismograms show a repeatable behavior in the repeatability metrics sections.
Figure 3.19: The repeatability metrics sections for component 2 of the shot 1630535 in the top and the seismograms from survey 1 (left) and from survey 2 (right) for this shot in the bottom. In the top left is the NRMS difference section and in the right is the SDR attribute section. The turning S-waves that appear around 1.5s in the seismograms show a repeatable behavior in the repeatability metrics sections, specially in the SDR section.
Figure 3.20: The repeatability metrics sections for component 2 of the shot 1630549 in the top and the seismograms from survey 1 (left) and from survey 2 (right) for this shot in the bottom. In the top left is the NRMS difference section and in the right is the SDR attribute section. The downgoing S-waves that appear around 0.8s in the seismograms show a repeatable behavior in the repeatability metrics sections.
Figure 3.21: The repeatability metrics sections for component 2 of the shot 1660532 in the top and the seismograms from survey 1 (left) and from survey 2 (right) for this shot in the bottom. In the top left is the NRMS difference section and in the right is the SDR attribute section. The downgoing S-waves that appear around 0.8s in the seismograms show a repeatable behavior in the repeatability metrics sections.
Figure 3.22: The repeatability metrics sections for component 2 of the shot 1690536 in the top and the seismograms from survey 1 (left) and from survey 2 (right) for this shot in the bottom. In the top left is the NRMS difference section and in the right is the SDR attribute section. The turning S-waves that appear around 1.5s and 2.0s in the seismograms show a repeatable behavior in the repeatability metrics sections.
CHAPTER 4
GEOMETRY ERRORS

There are several factors that can affect the repeatability of land 4D seismic data. One of the factors that has a significant impact on the repeatability of time-lapse seismic projects is the difference in the geometry of successive 4D seismic surveys. Because of this, in time-lapse studies it is important to repeat the acquisition geometry as much as possible. Landro (1999) states that repeated 3D VSP surveys (preferably using permanently installed geophone arrays) might be an efficient tool for detailed and precise monitoring of fluid and pressure changes within a hydrocarbon reservoir.

In this context, geometry errors are related to differences in the source and receiver positions between time-lapse surveys. As the raypaths for a given reflection point change by changes in source and receiver positions, then the transmission responses change due to different scattering and reverberations (Calvert, 2005). The impact of these changes in the repeatability of time-lapse data depends upon the degree of overburden heterogeneity.

In this case, a permanent seismic array was used. Several benefits can be obtained from using a permanent seismic array. Some of them are related to the fact that it simplifies the issue of repeatability and allows time-lapse repeat surveys to be conducted at a much-reduced incremental cost. It simplifies the issue of repeatability by eliminating variance in receiver position and orientation (Cornish et al., 2000). Another important advantage in using permanent receivers is that the positioning issue is resolved for the receiver side, and all attention related to repeating the geometry is focused on the source side (Landro & Skopintseva, 2008).

The goal of this chapter is to quantify the impact of source and receiver position differences between repeated surveys in seismic data repeatability. I intend to give some insight into how much repeatability is affected by positioning inaccuracies of the source and receiver
locations.

The sources of time-lapse VSP surveys should ideally be located exactly at the same positions to reliably monitor reservoir changes due to CO₂ injection. However, in practice this is rarely possible, since there is often some uncertainty in source locations during time-lapse data acquisitions (Zhang et al., 2010). Some graphics were plotted in order to show how repeatability changes with source positioning inaccuracies. These plots present the repeatability metrics (NRMS difference and SDR attribute) versus acquisition geometry errors.

Also in this chapter, some errors in the receiver orientations were simulated in order to investigate how repeatability is affected by errors that may be generated when the borehole array is not permanent. This analysis also involves graphics that show the repeatability metrics (NRMS difference and SDR attribute) versus errors in the receiver orientation.

All the analyses in this chapter were made for component 1 of the receivers.

### 4.1 Source positioning error

In order to accurately detect small changes due to production and injection effects within the reservoir, the sources of time-lapse multicomponent VSP surveys must be located exactly at the same positions. However, in practice, the source locations can vary from one survey to another survey.

The total number of shots acquired during the surveys in this study, that are common for both surveys, is 932. By analyzing the shotpoints for both surveys on a map (Figure 1.4), it is observed that some shot locations are really close to one another and other shot locations present differences in positioning from one survey to the other. This geometry provides data to study how repeatability changes with inaccuracies in source positions.

Firstly, all shots were sorted into groups according to their positioning error. One group consists of shots with separation distances less than 5ft, another group with shot separation distances between 5 and 10ft, the other group with shot separation distances between 10ft and 15ft and so forth. Figure 4.1 shows the histogram of the number of shots versus the
difference in source positions between both surveys.

The first observation one can make about the histogram shown in Figure 4.1 is that most of the shots have differences in source positions less than 10ft. Just few shots present a difference in position larger than 10ft. This implies that in terms of source positioning these data do not present many errors in geometry and are quite repeatable.

Figure 4.1: Histogram of the number of shots versus difference in source positions (ft). Most of the shots have difference in source positions less than 10ft. Just a few shots present a difference in position larger than 10ft.

To evaluate how the source geometry errors affect the repeatability of time-lapse seismic data, graphics that show the repeatability metrics (NRMS difference and SDR attribute) versus the difference in source positions were plotted. Just the first arrivals were used in this analysis because they are the least contaminated from other waves and have higher signal-to-noise ratio. The repeatability metrics were calculated for corresponding pairs of traces from both surveys in a window of 200ms around the direct downgoing wave.

Figure 4.2 and Figure 4.3 show the graphics for the NRMS difference and the SDR attribute versus differences in the source positions, respectively. Some observations one can make from these plots are that, the NRMS difference increases with increasing the difference in source positions and the SDR attribute decreases with increasing difference in
source positions. This work confirms that, as expected, larger geometry errors produce less repeatable data. The straight lines in the plots correspond to the linear best-curve fitting found using the linear least-squares methodology. As stated before, the least-squares fitting is a mathematical procedure for finding the best-fitting function to a given set of points by minimizing the sum of the squares of the offsets ("the residuals") of the points from the curve (Weisstein, n.d.). Straight lines ratify the fact that the NRMS differences increase and that the SDR attribute values decrease with difference in source positions. Thus, it is possible to see that even differences in the source positions around 30 ft affected the repeatability of this land VSP seismic data.

![NRMS differences vs difference in source positions](image)

**Figure 4.2:** Graph that shows the NRMS difference versus the difference in source positions. The red straight line corresponds to the linear best-curve fitting found using the linear least squares methodology. NRMS difference increases with increasing the difference in the source positions.

Significant changes in the repeatability after processing may result from changes in shot and receiver positions as small as 32 ft (Calvert, 2005). A 32 ft difference in shot position more than doubles the non-repeatability and a 64 ft difference triples it (Landro, 1999). In this case, just a few shots have a difference in source position greater than 25 ft. Thus, it is hard to estimate the difference in shot position that can cause a significant impact.
Figure 4.3: Graph that shows the SDR attribute versus the difference in source positions. The blue straight line corresponds to the linear best-curve fitting found using the linear least squares methodology. SDR attribute decreases with increasing the difference in the source positions.

Figure 4.4 and Figure 4.5 show the graphics with larger difference in source positions. It is clear from these plots that the NRMS difference increases and that the SDR attribute decreases with difference in source positions, or, in another words, that larger geometry errors produce less repeatable data. An error in the source acquisition geometry of 165 ft can severely impact the repeatability in land time-lapse seismic studies. Due to lack of data,
there is no information about the repeatability for difference in source positions larger than 35 ft and less than 150 ft.

![Figure 4.4](image)

Figure 4.4: Graphic that shows the NRMS difference versus the difference in source positions. Larger differences in source position were used in this analysis. The red straight line corresponds to the linear best-curve fitting found using the linear least-squares methodology. NRMS difference increases with increasing the difference in the source positions.

It was shown in Chapter 3 that the NRMS map (Figure 3.3) had localized anomalies that were related to punctual events that appeared on the time-shift map (Figure 2.10). Some questions can now be raised: What can be causing these localized anomalies in the NRMS maps? Are these events related to variable source timing between both surveys or to errors in the acquisition geometry? In order to answer these questions, some points with the greatest difference in source positions that generate large values for the NRMS difference were highlighted in the NRMS difference map, as shown in Figure 4.6. It is possible to see in this figure that some of the localized anomalies presented in the NRMS difference map are related to errors in the acquisition geometry. This is reasonable to expect, since errors in the geometry can cause time-shifts between data from both surveys and, as stated before, the NRMS difference is sensitive to time-shifts. These localized anomalies are not presented in
Figure 4.5: Graphic that shows the SDR attribute versus the difference in source positions. Larger differences in source position were used in this analysis. The blue straight line corresponds to the linear best-curve fitting found using the linear least-squares methodology. SDR attribute decreases with increasing the difference in the source positions.

the SDR attribute map (Figure 3.10). Therefore, the NRMS difference map is more sensitive to differences in source positions between successive surveys than the SDR attribute map. The other localized anomalies in the NRMS difference map that are also related to punctual events on the time-shift map, are probably related to variable source timing between both surveys.

4.2 Receiver orientation error

A permanent seismic array was used in the acquisition of the multicomponent VSP data used in this project. Permanently installed receiver systems have long-term advantages for repeated monitoring of production data in the oil field. Permanent deployment simplifies the issue of repeatability and reduces the cost of repeated monitoring surveys. Another important advantage in using permanent receivers is that the positioning issue is resolved for the receiver side, and all attention related to repeating the geometry is focused on the source side. Despite this fact, the adoption of the permanent seismic acquisition system is
still slow. A commonly accepted explanation for this fact is related to the difficulties and uncertainties associated with the cost-benefit for new fields. The smaller the field, the less the benefit compared to the up-front cost to establish a permanent receiver array (Landro & Skopintseva, 2008).

In general, differently placed receivers will record different wave-fields (due to changes in frequency, direction and strength of each wave-field component) and will respond differently to the same positional error (Naess, 2006).

As stated in chapter 2, 3D multicomponent VSP data are recorded with receivers made of three mutually orthogonal geophones. One geophone is oriented toward the vertical direction, whereas the two others are free to orient toward any arbitrary direction in the horizontal
plane. The process used to orient the horizontal components of the geophones to the same coordinate system is based on hodogram analysis. This process has an inherent error associated with it. Thus, it is impossible to find the exact orientation that the horizontal components of the buried receivers have under the subsurface. The greatest advantage in using permanently installed geophones is that the error intrinsic to this process is the same for the rotated data from both surveys. Therefore, after tool orientation the horizontal components of the geophones for both surveys may not be rotated to the exact orientation that the horizontal components of the buried receivers have under the subsurface, but they are going to have the same orientation for both surveys, simplifying the issue of repeatability. On the other hand, when the receivers are not fixed in place, the errors intrinsic to this process are not the same. So, after the tool orientation the horizontal components of the geophones are not going to have the same orientation for both surveys, which clearly affects the repeatability between datasets.

To better understand the relation between the errors in the receiver orientations and the repeatability, some errors were added in the rotation process to simulate the case in which the receivers are not permanently installed in place. This study was made in two different ways. Firstly, just survey 1 was used in the analysis. The data from survey 1 was rotated with the estimated orientation angles. Then, this same data from survey 1 was rotated with the estimated orientation angles added from 1 to 10 degrees, in order to simulate errors in the rotation process that occur when the receivers are not cemented in place. Then, the repeatability metrics (NRMS difference and SDR attribute) were calculated for the comparison between the first data rotated with the estimated orientation angle with the data rotated with the incorrect orientation angles. Plots that show the repeatability metrics versus the shot index for all the 10 comparisons were computed and are presented in Figure 4.7 and Figure 4.8. Since just data from survey 1 were used in this first case, the only non-repeatability factor involved in this analysis is the error in the receiver orientation.
Some observations can be made from Figures 4.7 and 4.8. First of all, as expected, the plots show that the repeatability decreases with increasing the error of the orientation angle used in the rotation process. The NRMS difference plot shows that for each degree difference in the orientation angle, the NRMS difference increases approximately 0.25%. Even though the SDR attribute decreases when the difference in the orientation angle increases, the repeatability decreases. The SDR attribute plot seems to be less sensitive to errors in the receiver orientation than the NRMS difference. The magnitude of the changes in the SDR attribute due to the errors in the receiver orientation is very low. In both plots, the differences in the repeatability metrics are higher for a region in which the shot index varies from 550 to 850. One explanation for this observation is related to the fact that the direct downgoing S-waves are present for the shots in this region and they are more affected by the rotation process.

Continuing this study, the data from survey 1 were rotated with the estimated orientation angles while the data from survey 2 were rotated with the estimated orientation angles added from 1 to 10 degrees. Then, the repeatability metrics (NRMS difference and SDR attribute) were calculated for the comparison between the first data from survey 1 rotated with the estimated orientation angle with the data from survey 2 rotated with the incorrect orientation angles. Plots that show the repeatability metrics versus the shot index for all the 10 comparisons were computed and are presented in Figure 4.9 and Figure 4.10. Just to emphasize the non-repeatability related to the error in the receiver orientation, the repeatability metrics in these plots were computed by the repeatability metrics in the case in which the data from survey 1 are rotated by the correct estimated orientation angle and the data from survey 2 are rotated with the incorrect orientation angles added from 1 to 10 degrees minus the repetability metrics for the case in which both data from survey 1 and from survey 2 are rotated with the correct estimated angles. In this case, since data from survey 1 and data from survey 2 are being used, all the factors that can affect repeatability in land seismic data are present.
By analysing Figures 4.9 and 4.10, one can see that the magnitude of the difference of the repeatability metrics is lower in this case when data from survey 1 is compared with data from survey 2 with the incorrect rotations than in the case that data from survey 1 is compared with data from survey 1 with the incorrect rotations. This observation could lead the reader to think that in this case the data are less affected by the receiver orientation errors since the variations in the repeatability metrics are lower. In both plots, there are events in which the difference in the NRMS difference is negative and the difference in the SDR attribute is positive implying that the case in which the data are rotated with the wrong angles are more repeatable than the one in which the data are rotated with the correct angles. This discrepancy happens because in this case, all the factors that can cause non-repeatability in the data (Figure 1.5) are present in the data. Therefore, it is not possible to separate in the values found for the repeatability metrics just the influence of the errors in the receiver orientations.

To conclude, when the receivers are not permanently installed in place, errors in the orientation of the horizontal components of the geophones may occur. These errors affect the repeatability in land seismic data. Because of this, in time-lapse VSP projects, since the cost of using permanently receivers is not as high as in surface seismic acquisition, the use of permanent seismic geophones is strongly advised.
Figure 4.7: Graph showing the NRMS difference versus shot index for orientation angle errors from 1 to 10 degrees. The NRMS difference was calculated for the data from survey 1 rotated with the estimated orientation angles with the data from survey 1 rotated with the estimated orientation angle added from 1 to 10 degrees. The only non-repeatability factor involved in this study is the error in the receiver orientation. The repeatability decreases with increasing the error of the orientation angle used in the rotation process.
Figure 4.8: Graph showing the SDR difference versus shot index for different orientation errors from 1 to 10 degrees. The SDR attribute was calculated for the data from survey 1 rotated with the estimated orientation angles with the data from survey 1 rotated with the estimated orientation angle added from 1 to 10 degrees. The only non-repeatability factor involved in this study is the error in the receiver orientation. The repeatability decreases with increasing the error of the orientation angle used in the rotation process.
Figure 4.9: Graph showing the NRMS difference versus shot index for different orientation errors from 1 to 10 degrees. In this plot the vertical axis is given by the NRMS difference calculated for the data from survey 1 rotated with the estimated orientation angles with the data from survey 2 rotated with the estimated orientation angles added from 1 to 10 degrees mines the NRMS difference found for the data from survey 1 and from survey 2 rotated with the estimated orientation angles. All the non-repeatability factors are involved in this study. In general, the repeatability decreases with increasing the error of the orientation angle used in the rotation process.
Figure 4.10: Graph showing the SDR difference versus shot index for different orientation errors from 1 to 10 degrees. In this plot the vertical axis is given by the SDR attribute calculated for the data from survey 1 rotated with the estimated orientation angles with the data from survey 2 rotated with the estimated orientation angles added from 1 to 10 degrees mines the NRMS difference found for the data from survey 1 and from survey 2 rotated with the estimated orientation angles. All the non-repeatability factors are involved in this study. In general, the repeatability decreases with increasing the error of the orientation angle used in the rotation process.
CHAPTER 5
DIFFERENCES IN THE NEAR-SURFACE CONDITION AND AMBIENT NOISE

The quality of land seismic data suffers from irregularities within the near surface, which is composed of layers that have experienced varying degrees of weathering. Examples of these irregularities include: lateral variation in thickness, lateral and vertical velocity variations, rugged topography, karst structures, and effects of near-surface water. The effects of these irregularities on seismic data include: statics, scattering, multiples, ground roll, weak penetration of signal into deeper layers, and severe amplitude losses (Al Jabri, 2011).

Different from surface seismic data, multicomponent VSP data detects seismic waves that are affected by the near surface layer only in the surroundings of the source of energy and not in the receiver. A direct implication of this fact is that the VSP data are less impacted by the near-surface effects since the seismic waves in these data just pass through the near surface layer one time. Besides this, downgoing P-waves acquired in VSP data can be a reliable source of information about the evolution and attenuation of the seismic wavelet.

In this chapter, the multicomponent VSP data acquired in Delhi Field will be used to investigate land seismic repeatability due to changes in the near surface conditions. In this case, the near surface conditions varied from survey-to-survey due to changes in soil saturation. When the first survey was acquired, the soil was wet, while when the second survey was acquired the soil was dry. It is expected that the attenuation and also the velocity of seismic waves in both surveys should be different due to changes in the water saturation. Time-shift maps and amplitude spectral ratio maps will be estimated for both surveys to quantify the relative contribution of this factor into the overall non-repeatability of 4D surveys.

The level of ambient noise related to wind, rain, or local traffic is much higher in land surface seismic data than in land VSP seismic data. It is expected to have less ambient noise
affecting VSP data because the geophones are buried. The ambient noise presented in VSP data usually comes from the source. This chapter will also include an analysis of the effect of the ambient noise on the level of repeatability in land seismic data. The ambient noise will be analyzed using signal-to-noise ratio attribute sections.

5.1 Near surface conditions

Guevara (2000) defines the near-surface layer: The near-surface layer (NSL) of the earth originates from the weathering of in-situ rocks and other environmental processes, such as transport and deposition of sediments. Its thickness is often a few tens of meters, although frequently its interface with the intact rock is not clearly defined. The NSL is usually less compacted, more heterogeneous, geometrically more complicated, and more porous than the consolidated rock below it. Due to these singular characteristics, the near-surface layer generates unique changes in the seismic waves coming from deeper layers. These changes affect the information from geologic targets carried by propagating waves, sometimes in a very detrimental way.

The near surface layer is also known as low-velocity layer (LVL). Sheriff & Geldart (1995) indicate five effects of the LVL on seismic waves:

- (1) high absorption of seismic energy;
- (2) traveltimes affected by the low velocity and the rapid space variation of the LVL properties;
- (3) shorter wavelengths, hence smaller features produce significant scattering;
- (4) the marked change in velocity at the base of the LVL results in wave propagation being nearly vertical (small range of values), regardless of its travel direction beneath the LVL;
- (5) the high impedance contrast at the base of the LVL makes it an excellent reflector, and produces multiple reflections and mode conversions.
From Guevara (2000) and Sheriff & Geldart (1995) definitions, it is possible to conclude that near-surface layer can be a cause of problems in time-lapse seismic projects, due to the fact that differences in the near-surface conditions may occur from one acquisition to the other, resulting in different seismic responses and consequently affecting the repeatability between successive seismic surveys.

One of the principal causes of non-repeatability issues in land seismic data is related to temporal variations of the near surface conditions. In this case, the near surface conditions varied from survey-to-survey due to changes in soil saturation. When the first survey was acquired, the soil was wet, while when the second survey was acquired the soil was dry. Some consequences of the variation of the water saturation at the near surface is that it may change the seismic velocities and quality factors of absorption from one acquisition to the other, directly affecting the seismic signal (Al Jabri & Urosevic, 2010). Therefore, non-repeatability effects are expected between successive surveys due to wet and dry conditions of the near surface.

Due to the variation in the soil saturation at the near surface from one survey to the other, changes in the attenuation (absorption and scattering) and in the propagation velocities of seismic energy need to be evaluated to better understand the factor responsible for large seismic response differences observed between different surveys.

5.1.1 Changes in the velocities

As stated before, changes in the near surface conditions related to water saturation from one survey to the other may cause a direct impact on seismic repeatability due to changes in the seismic velocities and in the quality factors of absorption. An indirect way to observe the changes in velocities between successive surveys is by plotting time-shift maps. Some causes for time-shifts between successive surveys can be: variable source timing, errors in the acquisition geometry, different acquisition reference-time definitions and changes in the near surface conditions. Generally, the two first causes cited above are responsible for the localized events in the time shift maps and the third and fourth causes are responsible for
the general spatial distribution of the time-shifts in the map.

To better understand the changes in velocities between the successive surveys, time-shift maps were plotted for some receivers and all the shots. The picks were made in the first arrivals in the component 1 for both surveys. Then, these picks were subtracted from each other for corresponding traces from both surveys to compute the time-shift maps. Receivers 4, 12 and 18 were used to generate time-shift maps. Time-shifts were picked for different receivers in order to see if there is consistency between these maps.

Figure 5.1, Figure 2.10 and Figure 5.2 show the time-shift maps for receivers 4, 12 and 18, respectively. Some observations can be made by analyzing these maps. First of all, there is a consistency between the time-shift maps for all the receivers. All the maps show similar behaviors and almost the same range of amplitude. These maps imply that all receivers should be below the near surface layer, consequently the seismic rays should be passing through this layer in all the cases and the influence of the near surface variations is almost the same for all of the receivers depth levels. The shallower receivers 1, 2 and 3 could not be used in these analysis because, as shown in chapter 2, they have a low signal-to-noise ratio and consequently low repeatability. Localized anomalies appear in all the maps and, as demonstrated in chapter 4, these events are probably related to differences in the source positions and to variable source timing between successive surveys.

Another observation one can make from these maps is that, in general, time-shifts are positive in the north part of the maps and time-shifts are negative or zero in the south part of the maps. These maps were generated as the values for the first break picks for survey 1 minus the values for the first break picks for survey 2. Therefore, positive time-shifts imply that the first break time for survey 1 is greater than the first break time for survey 2, and consequently the velocity for survey 1 is less than the velocity for survey 2 and negative time-shifts imply that first break picks for survey 1 are less than first break picks for survey 2 and, consequently, the velocity for survey 1 is higher than the velocity for survey 2. From the studies in the literature (Al Jabri et al., 2011), the data collected during a wet season,
in general, present greater velocities than the data collected during the dry season. In this study, data collected during wet season have higher velocities in the southern part of the map and lower velocity in the northern part of the map if compared with data acquired during the dry season.

Figure 5.1: Time-shift map for receiver 4. These maps were generated as the values for the first break picks for survey 1 minus the values for the first break picks for survey 2, positive time-shifts (red) implies that the first break time for survey 1 is greater than the first break time for survey 2, and negative time-shifts (blue) implies the opposite.

5.1.2 Changes in the attenuation

Seismic attenuation is a fundamental property of rocks caused by absorption and scattering. The attenuation of seismic waves degrades the seismic resolution, complicates the quantitative analysis of seismic attributes and is more sensitive than velocity to some of the parameters such as lithology, porosity and pore fluid characteristics (Pramanik et al., 2000).

Changes in the near-surface conditions can affect the seismic repeatability of time-lapse seismic surveys. Variation of the water content at the near surface may change the seismic
Figure 5.2: Time-shift map for receiver 18. These maps were generated as the values for the first break picks for survey 1 minus the values for the first break picks for survey 2, positive time-shifts (red) implies that the first break time for survey 1 is greater than the first break time for survey 2, and negative time-shifts (blue) implies the opposite.

velocities and seismic quality factors from one acquisition to the other. The frequency characteristics of the seismic wavelet will be different in dry and wet periods of the year. Usually, a lower frequency content is observed during dry periods compared to wet periods because of changes in soil hardness. Therefore, typically the wet near surface provides better seismic energy transmission and a broader signal compared to the dry near surface.

In this study, the amplitude spectra present in chapter 2 shown that the data collected during the wet season (survey 1), in general, had higher frequency content than the data collected during the dry season (survey 2). Therefore, the difference in the absorption of energy by the near surface has a significant impact in the time-lapse seismic data in this field.
With a view to quantify the difference in the frequency content for the successive surveys due to changes in the near surface conditions, amplitude spectral ratio maps were created. These maps were computed by the median value of the amplitude spectra for all the receivers and for each shot from survey 1 divided by the median value of the amplitude spectra for all the receivers and for each shot from survey 2 for different frequency ranges. These results were produced with a window of 200 ms applied around the direct downgoing P-wave. The direct downgoing wave in VSP data provides reliable information about the evolution and attenuation of the seismic wavelet. Besides, it is the least contaminated wave and has a higher signal-to-noise ratio. These calculations were made for different frequency ranges in order to analyze whether the maps are consistent for all of them and to achieve more reliable results, less influenced by noise. Figure 5.3, Figure 5.4, Figure 5.5, Figure 5.6 and Figure 5.7 show the amplitude spectral ratio maps for the frequencies in the range of, respectively, 40 to 60 Hz, 50 to 70 Hz, 60 to 80 Hz, 70 to 90 Hz and 80 to 100 Hz.

Some observations can be made from the frequency ratio maps. First of all, the maps show the same anomalies for all the different frequency ranges implying that they are consistent with each other and consequently more reliable. Another observation is that most of the shots present a frequency ratio greater than one, meaning that the data from survey 1 have, in general, a greater frequency content than the data from survey 2. This is reasonable to expect, since usually the wet near surface provides better seismic energy transmission and a broader signal compared to the dry near surface. It is also noted that, in general, the frequency ratio is larger in the southern part of the map which suggests that in this region the absorption is higher than in the other regions of the surveys.

In chapter 3, Figure 3.10 showed the SDR attribute map. It was possible to see that some regions of this map present relatively low values for the SDR attribute, which is an indication of poor repeatability. In order to understand the causes for this non-repeatability regions in the SDR attribute map, Figure 5.8 is showing the SDR attribute map and the amplitude spectral ratio map side by side highlighting some regions in which the SDR attribute map
Figure 5.3: Amplitude spectral ratio map for the frequency in a range from 40 to 60 Hz. Most of the shots presented a frequency ratio higher than one, which means that the data from survey 1 have, in general, higher frequency content than the data from survey 2.

This presents less repeatable events. It is possible to note in this comparison that most of the regions in which the SDR attribute map presents relatively low values coincides with regions in which the amplitude spectral ratio is higher. Regions in which the amplitude spectral ratio is higher are associated with areas in which the absorption is also greater. This observation implies that the SDR attribute map is sensitive to differences in the near surface conditions associated with changes in the absorption pattern.

In chapter 3, Figure 3.11 showed the SDR attribute map and the NRMS difference section side by side highlighting the regions in which both maps present higher repeatable events. The curves highlighting these regions were also plotted in the time-shift map for receiver 12 and in the frequency ratio map for the frequency range of 50 to 70 Hz. Figure 5.9 shows these maps with these regions highlighted side by side. From this figure, it is possible to see that the regions in which the NRMS difference map and the SDR attribute map present
Figure 5.4: Amplitude spectral ratio map for the frequency in a range from 50 to 70 Hz. Most of the shots presented a frequency ratio higher than one, which means that the data from survey 1 have, in general, higher frequency content than the data from survey 2.

higher repeatable events coinciding with the regions in which the time-shift map has values closer to zero and the frequency ratio map has values closer to one. This observation implies that these regions are those in which there are little differences in seismic velocities and absorption between the successive surveys. Therefore, the near surface condition probably does not change in these regions of the map.

In conclusion, changes in the near-surface conditions, due to variable soil saturation, can produce changes in seismic velocities and in absorption from one acquisition to the other what will directly affect the repeatability between surveys. In order to reduce the impact of the variability of the near-surface conditions on repeatability it is necessary to acquire data during the same period of the year, if possible.
Figure 5.5: Amplitude spectral ratio map for the frequency in a range from 60 to 80 Hz. Most of the shots presented a frequency ratio higher than one, which means that the data from survey 1 have, in general, higher frequency content than the data from survey 2.

5.2 Ambient noise

The level of ambient noise related to wind, rain, or local traffic is larger in land surface seismic data than in land VSP seismic data. It is expected to have less ambient noise affecting VSP data because the geophones are buried. The ambient noise presented in VSP data usually comes from the source.

In order to quantify the impact of random noise during the recording process on repeatability due to ambient noise, sections of signal-to-noise ratio attribute were computed for some shots. These signal-to-noise ratio attribute sections were estimated between pairs of consecutive traces on each survey. This calculation was made using a sliding window of 120ms. The sections were smoothed using a Gaussian filter.
Figure 5.6: Amplitude spectral ratio map for the frequency in a range from 70 to 90 Hz. Most of the shots presented a frequency ratio higher than one, which means that the data from survey 1 have, in general, higher frequency content than the data from survey 2.

The signal-to-noise ratio attribute can be calculated using the following equation (Pevzner et al., 2011):

$$SN_i = \sqrt{\frac{[g_{i,i+1}]_{MAX}}{1 - [g_{i,i+1}]_{MAX}}}$$ (5.1)

where $i$ is the trace number, $g_{i,i+1}$ is the normalized cross-correlation function between $i$ and $i+1$ traces and $[g_{i,i+1}]_{MAX}$ is its maximum value. This equation allows us to obtain a signal-to-noise ratio assuming that noise is additive, uncorrelated and has zero mean value (Pevzner et al., 2011).

Figures 5.10 and 5.11 show the signal-to-noise ratio section for shot 1300570 from survey 1 and from survey 2, respectively. The first observation one can make is that the direct downgoing P-wave is the event that appears with the highest signal-to-noise value in the sections. It is a consequence of the fact that the direct downgoing waves usually have
Figure 5.7: Amplitude spectral ratio map for the frequency in a range from 80 to 100 Hz. Most of the shots presented a frequency ratio higher than one, which means that the data from survey 1 have, in general, higher frequency content than the data from survey 2.

Figure 5.8: SDR attribute map and amplitude spectral ratio map for the frequency range from 50 to 70Hz side by side highlighting some regions in which the SDR attribute map presents lower repeatable events and the amplitude spectral ratio map presents higher values.
stronger seismic signal in the records because they are the ones that have shorter ray-paths and consequently are less influenced by attenuation. The overall variation in the signal-to-noise ratio across the survey records cannot be clearly seen in this case. It is hard to tell which data present higher signal-to-noise ratios. The behavior of the signal-to-ratio sections did not provide a standard. For some shots, the data acquired during the wet season presented higher signal-to-noise ratio and for other shots the data acquired during the dry season presented higher signal-to-noise ratios. Some shots also presented almost the same signal-to-noise ratio values.

To better understand the effect of the ambient noise on repeatability, sections of repeatability metrics were plotted for the same shot shown in Figure 5.10 and Figure 5.11. Figure 5.12 and Figure 5.13 show the NRMS difference section and the SDR attribute section for shot 1300570, respectively. Based on these figures it is possible to see that, ambient noise occurring just before the first-breaks is related to low signal-to-noise ratio values and is not repeatable. Comparing the signal-to-noise ratio sections and the repeatability metrics sections, the downgoing P-waves that have greater signal-to-noise values correspond with
the events with greater repeatability. Another observation one can make is that the decrease in repeatability in the repeatability metrics sections can be correlated with the low values in the signal-to-noise ratio attribute sections. Therefore, even though the level of ambient noise is much higher in land surface seismic data than in land VSP seismic data, random noise can directly impact the repeatability between VSP time-lapse surveys.

Figure 5.10: Signal-to-noise ratio section for shot 1300570 from survey 1. The direct down-going P-wave has the highest signal-to-noise ratio in this section.
Figure 5.11: Signal-to-noise ratio section for shot 1300570 from survey 2. The direct down-going P-wave has the highest signal-to-noise ratio in this section.
Figure 5.12: NRMS difference section for shot 1300570. Ambient noise occurring just before the first-breaks is related to low signal-to-noise ratio values and is not repeatable.
Figure 5.13: SDR attribute ratio section for shot 1300570. Ambient noise occurring just before the first-breaks is related to low signal-to-noise ratio values and is not repeatable.
CHAPTER 6
CONCLUSIONS AND RECOMMENDATIONS

This chapter presents the conclusions of this work and recommendations for future studies.

6.1 Conclusions

Repeatability of 4D land seismic data is affected by several factors. The purpose of this onshore repeatability study is to quantify the relative contribution of each factor. The factors analyzed in this study were: source and receiver geometry inaccuracies, variations in the immediate near surface and ambient non-repeatable noise. Another goal of this project is to understand the advantages and disadvantages of the different repeatability metrics, normalized-root-mean-square (NRMS) difference and signal-to-distortion ratio (SDR) attribute, to evaluate the level of seismic repeatability between successive time-lapse seismic surveys. First of all, it is important to state that in order to retain the inherent effect caused by each factor that affects the repeatability of 4D land seismic data, no cross-equalization technique was applied in the data. Therefore, all the conclusions from this project are based on the raw data. The conclusions from this research include:

- Time-shifts exist between the successive multicomponent VSP surveys in Delhi Field. Some of the causes for these time-shifts were found to be related to errors in the geometry associated with difference in source positioning and variations in the near surface conditions due to differences in soil saturation.

- NRMS difference is dependent on time-shift, amplitude and phase differences and additive noise. Depending on the intensity of the time-shifts, it can be difficult to interpret NRMS values as representative repeatability indicators since they do not distinguish
between information about time-shift and information about amplitude and phase differences. In these 4D multicomponent VSP surveys in Delhi Field, time-shifts were present in the raw data and the NRMS map was totally driven by time-shifts.

- **SDR attribute** is dependent on amplitude and phase differences between traces from successive surveys. No correlation could be seen between the SDR attribute map and the time-shift maps. A good correlation could be seen between the SDR attribute map and the amplitude spectral ratio maps. This observation implies that the SDR attribute map can be a good source of information about differences in the near surface conditions associated with changes in the absorption pattern in time-lapse projects.

- In this study, it is shown that NRMS difference is greatly influenced by time-shifts and the SDR attribute is influenced by amplitude and phase differences between traces from successive surveys. Time-shifts can be estimated by subtracting the first-arrival times from both surveys or by using the time of the maximum cross-correlation. Therefore, SDR attribute combined with the time-shift maps might give more distinct and representative repeatability information than the NRMS difference alone.

- In these time-lapse multicomponent 3D VSPs in Delhi Field, the downgoing S-wave could not be observed for all the shots. This happened in most of the cases because the S-wave is slower than the P-wave, and for large offsets it reaches the geophones after the recording time. However, when the downgoing S-wave was present in the data, it showed in most of the cases, a highly repetitive behavior on the same order of magnitude as the downgoing P-wave. The downgoing S-wave for explosive sources is not controllable, so it cannot be used for imaging purposes. However, the fact that the downgoing S-wave generated by explosive sources and registered by VSP surveys, when present in the data, appears to be a repeatable event, implies that this kind of wave can be used in estimates of time-lapse properties as, for example, S-wave velocity and S-wave quality factors.
• In the 3D VSP surveys in Delhi Field, most of the shots have differences in source positions less than 10 ft. This implies that in terms of source positioning these data do not present errors in geometry and are quite repeatable. Repeatability changes with inaccuracies in source positions were analyzed and it was concluded that larger geometry errors produce less repeatable data. Differences in source positions around 30 ft affected the repeatability of this land VSP seismic data significantly. The impact of differences in source positions larger than 35 ft on repeatability could not be analyzed in this study due to lack of data. Therefore, differences in source locations should be avoided during 4D VSP acquisition in order to improve reliability of time-lapse VSP monitoring.

• Some of the localized anomalies presented in the NRMS difference map and related to greater time-shifts magnitudes were caused by errors in the acquisition geometry. As shown in this study the NRMS difference map is more sensitive to errors in the source and receiver geometry than the SDR attribute map.

• In the acquisition of these 3D VSP surveys in Delhi Field, a permanent seismic array was used. It is known that permanently installed receiver systems improve the repeatability in time-lapse seismic studies. Errors in the receiver orientations were added in the data to simulate the case in which the receivers are not permanently installed. It was shown that the repeatability decreases with increasing error of the orientation angle used in the rotation process. In the case in which the only non-repeatability factor involved in the analysis was the error in the receiver orientation, the NRMS difference plot shows that for each degree difference in the orientation angle, the NRMS difference increases approximately 0.25%. Therefore, when the receivers are not in place, errors in the orientation of the horizontal components of the geophones may occur. These errors affect the repeatability in land seismic data. Because of this, in time-lapse VSP projects, since the cost of use permanently receivers is not as high as in surface seismic
acquisition, it is strongly advised to use permanent seismic arrays.

- Changes in the near surface conditions related to water saturation from one survey to the other may cause a direct impact on seismic repeatability due to changes in the seismic velocities and in the quality factors of absorption. In order to reduce the impact of the variability of the near-surface conditions on repeatability it is necessary to acquire data during the same period of the year. Time-shift maps and amplitude spectral ratio maps seemed to be a reasonable way to quickly evaluate these changes associated with differences in the near surface condition in time-lapse surveys.

- The 3D multicomponent VSP data from survey 1 contained for most of the shots higher frequency content than the data from survey 2. Survey 1 was acquired when the soil was wet and survey 2 was acquired when the soil was dry. A wet near surface provides better seismic energy transmission and a broader signal bandwidth compared to the dry near surface.

- There was a good correlation between the NRMS difference map and the SDR attribute map in the regions in which the repeatability was higher. The regions in which the NRMS difference and SDR attribute maps present higher repeatable events coincide with the regions in which the time-shift map had values closer to zero and the frequency ratio map had values closer to one. This observation implies that there were regions in which differences in seismic velocities and absorption between the successive surveys were less or non-existent.

- Even though the level of ambient noise is much higher in land surface seismic data than in land VSP seismic data, it is shown that random noise present in the data also affects the repeatability of the VSP time-lapse surveys in Delhi Field.

- The direct downgoing P-wave is the event with the highest signal-to-noise ratio attribute. It is a consequence of the fact that the direct downgoing waves usually have
stronger seismic signal in the records because they are the ones that have shorter ray-paths and consequently are less influenced by attenuation.

• It is strongly advised to use the SDR attribute map and the time-shift maps together for the raw data prior to any time-lapse processing to see where the repeatability issues are present in the data and consequently to give an insight into which regions of the data require special attention in processing. The combination of the SDR attribute map with the time-shift map should assist in showing regions in which non-repeatability factors have a significant impact on the time-lapse surveys.

6.2 Recommendations

Additional work could be undertaken based on the results of this thesis. A number of areas for potential future work are:

• The factors that can affect the repeatability in a land seismic data studied in this thesis were: source and receiver geometry inaccuracies, variations in the immediate near surface and ambient non-repeatable noise. Another significant factor that affects the repeatability of land seismic data and that was not analyzed in this study was the differences in seismic signature between time-lapse surveys. There is a lack of information in the literature about this topic specially for cases in which explosive sources are used. Studies to show how repeatability of land seismic data are affected by variations in the source signature between time-lapse surveys should be conducted.

• No analysis was made to evaluate whether the change in soil saturation from one survey to the other could have any impact on anisotropy. It is known for this Delhi study area that in the shallow layers the presence of anisotropy is not significant. Therefore, differences in the near surface conditions related to soil saturation probably do not cause significant changes in the anisotropy parameters. Studies could be done for data that demonstrate significant anisotropy in the shallower layers in order to show how
variations in the near surface impact the anisotropy and consequently the repeatability between time-lapse surveys.

• In this study the direct downgoing S-wave generated by an explosive source apparently is a repeatable event in time-lapse seismic records. Studies should also be done to evaluate the kind of information the downgoing S-waves generated by explosive sources can add in a time-lapse seismic project.

• Processing can directly affect repeatability in time-lapse seismic data. Studies could be done in order to evaluate the impact of each processing step on the general repeatability of 4D surveys.

• For reservoir imaging purposes, these 3D multicomponent VSP surveys have some limitations: the length of the receiver array is short and it is placed in the shallower depths far away from the reservoir. This fact made it really difficult to study the impact of the factors that can affect the repeatability of land time-lapse seismic data directly in the reservoir.
REFERENCES CITED


Oghenekohwo, Felix, & Herrmann, Felix J. 2013. Assessing the need for repeatability in acquisition of time-lapse data. *In: CSEG.*


