Sensitivity analysis of acquisition parameters in seismic tomography

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Abstract

The result of a seismic tomography campaign relies heavily on the acquisition grid composed by pairs of source-receivers. However, the influence of the grid's geometry is not quantified which poses a problem to the optimization of the methods.

To infer the sensitivity of the tomographic result regarding the geometry of acquisition, a series of surveys were conducted on a gypsum cube. The data acquisition was made experimentally, by preparing the body; creating the grid for exact placing of sources and receivers; surveying using seismic waves generated using apparatus created for this study and the first arrivals were picked from the recorded data through signal analysis using a threshold to avoid excessive noise. Following, the modelling was conducted via SIRT, creating velocity models by seismic inversion. For the sensitivity analysis different receivers' grids (configurations) were used, divided in three testing scenarios: grid density, receiver placement and depth's influence.

It is proven with this work, that the position of the recording sensors impacts the result of the inversion algorithm - the velocity model. It is shown that a denser grid density, with receivers placed directly across the anomaly in a homogenous area provides the best outcome. The simple inversion algorithm proved great capacity to create the velocity models from the acquired data however, due to its simplicity the presence of high frequency noise in the signal, caused by bad adherence from the receivers and perturbances caused by the environment in which the surveys were conducted, masked some of results.

Keywords: seismic tomography, geometry of acquisition, first arrival, seismic inversion, sensitivity analysis.

1. Introduction

With most of the already discovered ore deposits being extracted there is a global need for new extraction sites to answer the increasing demand for these materials. This search for resources requires a great level of certainty due to the time and cost of the operations. The geophysical studies applied to the areas of interest are usually seismic surveys using pairs of sources and receivers to register the changes in the wave's propagations velocity and infer the presence (or lack of) anormal data, usually related to ore deposits and reservoirs.

The main interest of an exploration campaign is to locate the presence of anomalies and defined them to guarantee a certain level of certainty for the extracting phase. This search, from an economical and business point of view, is preferably conducted with the least amount of equipment (in this case, sensors). This aspect creates the necessity for the optimization of the data acquisition phase which can be achieved by understanding the influence that different acquisition geometries display on the results of acoustic tomography inversion.

2. Methodology

A series of surveys in order to understand the wave's propagation characteristics took place using a physical model – a hand-made gypsum cube – and several piezoceramic sensors each time (one, functioning as a source trigger and three receptors, on opposing faces of the model) used to measure the propagation velocity (P-waves and S-waves, separately) inside the cube. The laboratorial work captured the behaviour of P-waves and S-waves on a solid body and its utility, regarding tomography, with emphasis on the propagation's velocity. The acquired data was recorded by a software and processed using different algorithms. The methodology for this work was divided into four successive sections.

2.1. Data acquisition

The data acquisition started by scraping the cube to remove exceeding material from its faces resulting from coupling materials used to connect the sensors. Besides that, some areas of the cube were damaged and/or skewed so a second patch work took place. After completing the restoration work, the cube's final measures were $49{,}5 \times 49{,}4 \times 48{,}7\ cm$ out of gypsum with exception for for a small, almost spherical, cavity located within the cube with 15 cm in diameter and centred on $24{,}8 \times 24{,}7 \times 24{,}4\ cm$ acting as an anomaly. Knowing the location of the cavity is a key element to this whole study since it allows to confirm the results when the model for the anomaly is created. With the cube's faces prepared for surveying it was possible to mark the sensor's positions. With the objective of covering the most area possible a 17 by 17 grid was created (Figure 1) leaving a frame of safety around it since the edges of the cube were damaged and could possibly endanger the propagation of waves in that area.

Figure 1 - Cube's acquisition 17x17 grid (photo)

The data was acquired using a set of 4 piezometric sensors. Due to the sensor's specifications it is possible to convert the mechanic energy created by the spring device in an electric signal. The data is recorded in a computer by connecting the sensors to an oscilloscope that works as a link between said sensors and the software. The oscilloscope used was a *PicoScope*, model 2406B, which transfers the data to the computer through a specific software, *PicoScope 6.* The software allows the visualization of each waveform (one per sensor, allowing a visual quality control) and some of the wave's characteristics, depending on the settings. The settings for the recording of the data are as follows:

- 100 ms/div, totalling on 1s of sampling
- 1 million samples
- Pre-trigger at 0%, making the recorded data start (t=0 ms) simultaneously with the trigger
- Trigger at 20 mV, indicating the minimum amplitude value to start recording the wave.

For each survey, there is 1 source and 289 receivers which represents 97 shots per survey, since each signal is captured by 3 receivers, in different positions and 10 surveys per wave type.

2.2. Picking algorithm

Having finished the surveys, the data is dispersed into 970 files per wave type. Therefore, in order to have the information organized and to facilitate the following procedures in this work an Excel file is created with the specific coordinates for each sensor and the name of each file (one file per shot). To register the arrival of each wave to the designated sensor one must define what should be considered an arrival. A significant disturbance registered by a receptive sensor is marked as an arrival when it presents an amplitude equal or higher than a specific value pre-determined by the user in the software. The trigger value used was 20 mV.

This algorithm works by analysing the raw data from the surveys. It starts by reading the file with all the information and proceeds to identify, open and read all the information contained in each file, registering the time differences between each arrival and the trigger. At the end, each time difference is displayed in the original file for further analysis.

For this study, to avoid high levels of noise present in the signal, the threshold used represented 40% of the maximum amplitude of each wave, identifying the first arrival of the wave. The process from collecting the data until the first arrival is determined can be viewed in the following schematic (Figure 2).

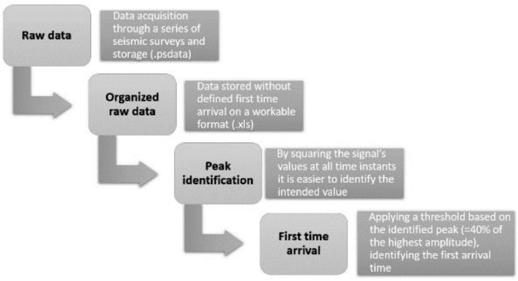

Figure 2 - First arrival time picking flowchart

2.3. Inversion algorithm

The algorithm for first arrivals tomography created by Mendes (2008) [1] uses as an input the data resulting from the picking algorithm and outputs a velocity model and numerous variables used to quantify the quality of the results. The inversion algorithm applied to this study makes use of the previously explained simultaneous iterative reconstruction technique (SIRT).

First, the background velocity is estimated by a Monte Carlo inversion and secondly, the final velocity model is built by refraction tomography. The Monte Carlo inversion is a two-step process: firstly, the traveltimes are computed through the initial model (m_0) following the velocity function's logs are randomly perturbed creating a new velocity model (m_k). It is then applied a misfit function (E_k) with:

$$\boldsymbol{E}_{(\boldsymbol{m_0})} = \frac{\mathbf{1}}{\mathbf{2N}}\left(\sum_{i=1}^{N}(\boldsymbol{t_i}^{obs} - \boldsymbol{t_i}^{calc})^2\right)$$

Where N represents the number of source-receiver pairs, t_i^{obs} and t_i^{calc} are the observed and calculated traveltime data, respectively. If the condition $E_k < E_{k-1}$ is sufficed, m_k is accepted as current model; if not, m_{k-1} is kept as the current model and must be perturbed again. This process continues until a desired convergence level is reached or a determined iteration number is reached (Mendes, 2008) [1]. Following the proposed method for SIRT by Watanabe *et al.* (1999) [2], this algorithm associates a Fresnel volume weight for every cell to explain the residual traveltime and the first-order volume is a family of neighbouring diffracted rays delayed after the shortest traveltime.

$$\Delta\boldsymbol{\tau} = \boldsymbol{T_{SPR}} - \boldsymbol{T_{SR}} < \frac{\mathbf{1}}{\mathbf{2f}}$$

With f being the frequency, T_{SR} the shortest traveltime from source S to receiver R and T_{SPR} the traveltime for the diffracted ray through each cell P. According to Watanabe *et al.* (1999) [2] the Fresnel volume is characterized as a weighting function W, at cell P, regarding the delay time $\Delta\tau$ as:

$$\boldsymbol{W} = \begin{cases} \mathbf{1} - \mathbf{2f}\Delta\boldsymbol{\tau}, & \left(\mathbf{0} \le \Delta\boldsymbol{\tau} \le \frac{\mathbf{1}}{\mathbf{2f}}\right) \\ \mathbf{0}, & \left(\frac{\mathbf{1}}{\mathbf{2f}} < \Delta\boldsymbol{\tau}\right) \end{cases}$$

Although the result of this process is a velocity mode, the SIRT algorithm does not compute the velocity but rather the updated slowness S_{k+1}^{j}, according to the equation stated by Mendes (2008) [1]:

$$\boldsymbol{S}_{k+1}^{j} = \boldsymbol{S}_{k}^{j}\left(\mathbf{1} + \left(\sum_{i=1}^{N}\frac{\boldsymbol{W_{ij}}\Delta\boldsymbol{t_i}}{\boldsymbol{t_i}^{calc}}\Big/\sum_{i=1}^{N}\boldsymbol{W_{ij}}\right)\right)$$

Being N the total number of Fresnel wave paths crossing the j-th cell, $k+1$ represents the iteration number and Δt_i the difference between the picked time (t_i^{obs}) and the computed time (t_i^{calc}).

According to Mendes (2008) [1], the main feature of this SIRT is the assumption that the traveltime difference (Δt_i) is produced by the crossing of cell j by the Fresnel wave path i, with a weight defined by $P_j^{\Delta t_i} = \frac{W_{ij}}{\sum_{j=1}^{M} W_{ij}}$ with M being the number of cells on the grid.

To study the effect of a change in the acquisition geometry, some parameters must remain invariable. For that, the algorithm allows some characteristics of the model to be set such as:

- Number of shots = 10
- General grid size and referential origin (o) coordinates
    - nx = 55*2

- nx = 55*2
- nx = 55*2
- ox = 0
- oy = 0
- oz = 0

- Grid spacing = 0.005 m
- Number of iterations = 10

2.4. Sensitivity analysis

Having a working set of parameters, allows the analysis of the influence of different acquisition geometries on the result. Different characteristics of the acquisition grid may affect the result, such as:

- Area coverage: the area occupied by the receivers
- Grid density: the higher or smaller amount of space between adjacent receivers represent higher or lower density of the acquisition grid, respectively
- Receiver placement: specific location of each receiver

This analysis was divided into three separate scenarios so that the different changes on the geometry can be studied with focus on each type of change. For each test, the sources remain unchanged only varying the receiver's positioning.

The changes in geometry were applied after the full acquisition of data. Making use of *Matlab*'s capabilities, the different receivers can be turned on and off, according to the geometry in study. From the initial geometry (with 289 receivers), the new geometries turn off the effect of blocks of receivers creating different geometries to study the different characteristics previously exposed.

In sum, the different configurations are created not by repeatedly surveying the body in the laboratory but by digitally removing the receivers recording on specific positions, regarding the tests being performed.

The different scenarios 1, 2 and 3 intend to infer the effect of grid density, receiver positioning and depth on the result, respectively. Each scenario has different configurations that allow to compare and reach conclusions between the different geometries. The general characteristics of the different scenarios are organized in the following Table 1:

Table 1 -Scenario's description

	Configuration	No. Receivers	No. Sources	Distance Receivers	Distance Sources
Scenario 1	#1	578	10	2.5 cm	35 cm
	#2	292	10	5 cm	35 cm
	#3	18	10	20 cm	35 cm
	#4	10	10	35 cm	35 cm
Scenario 2	#5	162	10	2.5 cm	35 cm
	#6	416	10	2.5 cm	35 cm
Scenario 3	#7	306	10	2.5 cm	35 cm
	#8	306	10	2.5 cm	35 cm

The effect of the different geometries is analysed quantitatively by examining the convergence of the calculated and observed/acquired data and qualitatively by displaying key slices of the constructed velocity models.

3. Results

Overall, the algorithm provided good results, but the acquisition process shows some flaws regarding the quality of the signal. There is some noise on every signal which may have led to a decrease in the quality of the convergence by the inversion algorithm. On Table 2, is provided a complete analysis of the different scenarios. Some content in this table is colour coded from red (worse) to green (best), regarding the objective of this work.

Table 2 - Results from the different scenarios, colour coded to reveal significance of values

	Configuration	No. Receivers	No. Sources	Distance Receivers	Distance Sources	δx_i (s)
Scenario 1	#1	578	10	2.5 cm	35 cm	6.57E-10
	#2	292	10	5 cm	35 cm	5.24E-10
	#3	18	10	20 cm	35 cm	3.80E-10
	#4	10	10	35 cm	35 cm	1.24E-09
Scenario 2	#5	162	10	2.5 cm	35 cm	1.86E-10
	#6	416	10	2.5 cm	35 cm	3.17E-10
Scenario 3	#7	306	10	2.5 cm	35 cm	1.59E-10
	#8	306	10	2.5 cm	35 cm	1.36E-10

For each one of the three scenarios, respectively, it is possible to state that:

A bigger number of receivers, despite recording more information and covering the entire area with a denser grid, does not produce the best result possible as demonstrated by Configuration #1. However, having a configuration with a small number of recording points is also not an advisable procedure to conduct the survey as proven by Configuration #4. Although both configurations can cover the same area, the two extremes of grid density perform poorly when compared with more moderate approaches such as the cases of Configuration #2 and Configuration #3. It is of high importance to cover as much area as possible but high density may result in an overflow of information, slowing the process and affecting the results of adjacent receivers and a low density also performs not up to par, lacking information of key areas of the body. Qualitatively, all the configurations used in this scenario can identify and delineate the expected anomaly, showing the capacity to create good velocity models with the assigned configurations.

Since the location of the anomaly is the ultimate objective of a prospecting campaign, this scenario showed the importance of a well thought out placement of receivers. Having the location of the unknown volume in between the sources of the seismic waves and the area covered by the receivers, as demonstrated with Configuration #5, is fundamental for the identification of the intended anomaly However, focusing the recording of information on the area directly on top of an anomaly does not provide a clear delineation of the volume since no information is recorded outside of the anomaly's influence, having no barrier between different mediums. This is confirmed by Configuration #6, where the anomaly is well defined without any receivers placed on top of the anormal volume. Out of all eight configurations, Configuration #5 was the best configuration regarding the convergence and total number of receivers. It is however highly improbable to reproduce this configuration in a real situation given that the anomaly location is unknown before commencing the surveys and as mentioned before is not useful to delineate any anomaly being only able to confirm or deny the presence of a anormal volume in the are in study.

The third and final scenario was the least conclusive of the three. The difference in the result, probably due to the small scale of the experiment, between Configuration #7 and Configuration #8 is very slim. However, both these two configurations have the best convergence out of all eight. Leaning on the explanation provided earlier that the sedimentation of the grains of gypsum differs between the bottom half of the cube and the top, this result shows that the performance of a given geometry of acquisition is better in an homogenous body than otherwise. This statement is corroborated by the velocity models produced by both configurations where Configuration #8 clearly delineates the anomaly while Configuration #7 does not provide a clear shape to the volume.

The initial configuration of receivers (Configuration #1) displayed on Figure 3, presents the starting point of this work and on Figure 4 is shown the velocity model created with this configuration.

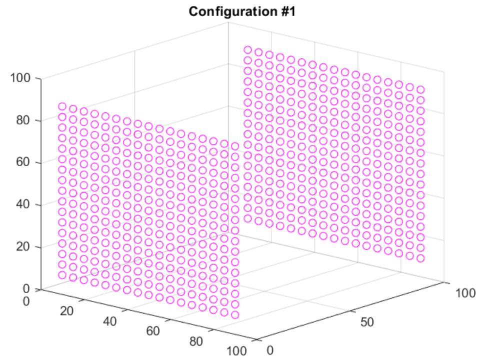

Figure 3 - Grid of receivers used on Configuraiton #1

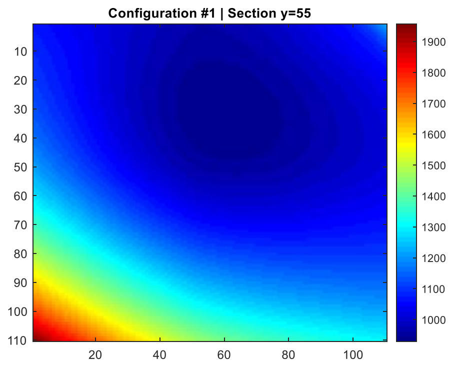

Figure 4 - Section y=55 from the velocity model for Configuration #1)

4. Conclusions

The aim of the present work was to access the implication of different acquisition geometries in the result of a seismic wave tomographic survey with the ambition of serving as an additional document in possible future prospecting campaigns, allowing a more knowledgeable placement of receivers.

With the experimental work developed and the theoretic background provided it is possible to state that the placement of the receivers and the different density of the acquisition grids produce a noticeable variation in the convergence between the observed/real data with the calculated/computed data.

In order to achieve the results, the 50x50x50 cube of gypsum was scraped, to smooth most of the areas of the faces and remove stains caused by previous studies; a grid of 17x17 was designed on each face to mark the exact positions of the receivers, 2.5 cm apart. After this preparation, the data was acquired (both p-waves and s-waves) with piezometric sensors and the information was later computed with a SIRT algorithm.

The outcome of a seismic wave tomographic campaign is susceptible to different acquisition geometries, variations on grid density and the body's physical and structural integrity. Through the results obtained by the developed work on p-waves, a quantification of the effect caused by the acquisition geometry is possible. By studying the influence of the different geometries in scenarios it was possible to analyse specific changes such as grid density, receiver positioning and the effect of depth, respectively. A velocity model containing a big number of receivers and consequent higher grid density presents a lacking convergence when compared with surveys conducted with a reduced number as proven by first scenario of testing. However, it is also noticeable in the first scenario of experiments that if the number of receivers reaches a value that does not allow the area to be sufficiently represented and therefore the convergence is bad, being the worse result out of all the configurations used. With this, it is favourable to use more receivers than less but if the coverage of the area in study is guaranteed, the grid composed by the different receivers may vary in accordance to resources available.

With the experiments conducted, mainly on the second scenario of testing, is was also established that much like what would be expected the placement of receiving sensors right across the anomaly, creating a direct path from a source of signal to a receiver, increases the quality of the convergence substantially. Being the anomaly the volume of body most heterogenous, a focus by the recording hardware on said volume is imperative to have a good representation of the volume. However, by not placing any receivers on the ideal area the data still shows an acceptable convergence but approximately three times worse than the ideal placement where the anomaly is covered in a dense grid of receivers. This came to prove an hypothesis cited in the objectives of this dissertation.

Finally, in the last scenario of testing for this dissertation, the receivers placed in a dense grid either in the top or bottom of the cube did not translate in a substantial variation on the final result. Therefore, no correlation was found between depth of recording and results. However, it showed that placing the receivers in a homogenous part of the of the body provides better results since the configurations covering either half of the cube showcased the best convergence.

The work conducted in this dissertation did not, however, contemplate all the proposed studies due to time constraints. The effect caused by different acquisition geometries was studied for S-waves, only P-waves. Although the methodology for recording S-waves has been created and the data properly recorded, all the computations necessary to produce some quantifiable results were not possible. In this note, some future works are suggested in two separate categories: with the model and data from this dissertation and with a different body.

To make use of the existent body – a gypsum cube – it is suggested to fill the volume without any matter (anomaly) with some material and run the same experiment to perceive if the computations are accurate enough to identify the anomaly when the difference in the waves' velocity is not as drastic the difference currently existent between gypsum and air. Using the already collected data, new configurations may be tried and/or retried with different variables to certify the results provided. Lastly with the data collected in regard to S-waves, since no computations were conducted for this study it would be interesting and an asset to analyse the behaviour of S-waves when faced with different geometries of acquisition and compare it to the demonstrated results for P-waves.

Regarding the body, the material used presented difficulties due to its physical degradation. While surveying, since for each source 97 shots were taken (for each wave type), the degradation of the cube was visible and in some cases difficulted and even made impossible some readings of the signal, causing the need for a constant repetition of shots resulting in more damage done to the cube and time lost. Also, the surface of the cube near the edges was rough, irregular, and degraded which made much more complicated the adherence of the sensors to the body. Besides the physical constraints of the gypsum cube, the adhesive used to fix the sensors in place for surveying also proved challenging at times. Due to the oscillation of temperature in the laboratory where the experiment was conducted, the viscosity of the Vaseline would diminish allowing the sensors to slide off and produce bad recordings or none. Also, given the repetitive nature of the experiment as previously mentioned, the adhesive used to fix a set of receivers would stain the cube, making the following surveys in those positions a lot harder since the Vaseline would not adhere as well to the face of the body.

Abandoning the current experimental cube, there are two routes that may be taken. Maintaining the scale of this work, a new body could be created in a material not so prone to degradation as gypsum allowing to repeat this study with a clearer outcome, without so much noise in the acquisition. If there is the possibility to upscale, taking this study to the field would be interesting to investigate if the outcome of the experimental work achieved in the laboratory would translate to a uncontrolled environment.

5. References

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