REFRACTION SEISMIC MODELING AND INVERSION FOR THE DETECTION OF FRACTURE ZONES IN BEDROCK

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Abstract

We have investigated the response of several synthetic models of variable complexity to tomographic inversion using Rayfract®. This software is fairly advanced and complex and offers many different options when inverting refraction seismic data. Using this program to investigate the detection of fracture zones in bedrock, its parameters may be roughly grouped in three categories: the inversion and weighting method used, whether single or multi-run will be employed and the intensity of smoothing. We have discerned that multi-run Conjugate Gradient inversion method, with Cosine-Squared weighting and a 2D Plus-Minus starting model can give fairly good results. Minimal smoothing is also essential for the quantitative characteristics of the detected zones to be accurately calculated, but this is a hyper sensitive procedure which may result in over or underestimations of zone velocity values. Generally, we have concluded that it possible to locate and characterize fractured zones in bedrock albeit with some limitations. It has been found that the imaging of the position and inclination of zones can be problematic especially when the zones are neighboring bedrock areas with small velocity contrast. The detectable depth extent of fracture zones can be followed to a certain depth, but deep zones give the same response as shallow zones due to geological noise. The width of the zone is almost always very accurate and overburden layers can be precisely defined when the interactive picking of branch points prior to inversion is carefully done. The velocity of a zone can be calculated with a good combination of inversion parameters. Moreover, as seen after reprocessing some of the Knappe tunnel data, tomographic inversion can pick up zones that cannot be interpreted traditionally. Finally, denser shot point spacing can bring about a noticeable improvement on the inversion results.

Introduction

The Geological Survey of Norway (NGU) has, in cooperation with the Norwegian Public Road Administration (NPRA), performed tomographic inversion of refraction seismic data. At the Knappe tunnel in Bergen, Norway, tomographic inverted refraction seismic and electric resistivity tomography (ERT) data were compared with bedrock quality observed during tunnel excavation. This comparison showed that ERT was slightly better than traditional refraction interpretation in pinpointing bad rock quality, and the latter slightly better than tomographic inversion. These interesting results motivated NGU to use modeling to study the capabilities and limitations of tomographic inversion of refraction seismic data. The goal is to try and identify patterns created by known models when moderately knowledgeable inversion schemes are used and in this way attempt to correlate geophysical anomalies with weak zones on real refraction seismic data, plan future studies and develop guidelines for the acquisition, inversion and reporting of refraction seismic data.

Software Description & Application

The software utilized was Rayfract® and its tomographic method is based on forward modeling refraction, transmission and diffraction (Lecomte et al., 2000) and back-projecting traveltime residuals along wave paths also known as Fresnel volumes (Watanabe et al., 1999) instead of conventional rays. Before we are able to run Wavepath Eikonal Traveltime or WET inversion (Schuster & Quintus-Bosz, 1993) though on either real or synthetic data, an initial model has to be generated. The program offers a series of means to derive a starting model such as 1D Gradient, Delta-tV, Hagedoorn's Plus-Minus or Wavefront method. In order to pick a preferable method, we revisit the results of inverting the Knappe tunnel data (Rønning et al., 2016). It was concluded that when possible to use Hagedoorn's Plus-Minus method (Hagedoorn, 1959) and create a 2D starting model, results are more consistent and tomograms more detailed. Regarding the inversion parameters, we put into practice the new multi-run feature which essentially performs a number of iterations (maximum 10) for a set of regularization parameters. Another important feature is the selection of Cosine-Squared weighting function as an alternative to Gaussian weighting that existed in previous versions. Finally, Conjugate Gradient and Steepest Descent inversion methods were also tested.

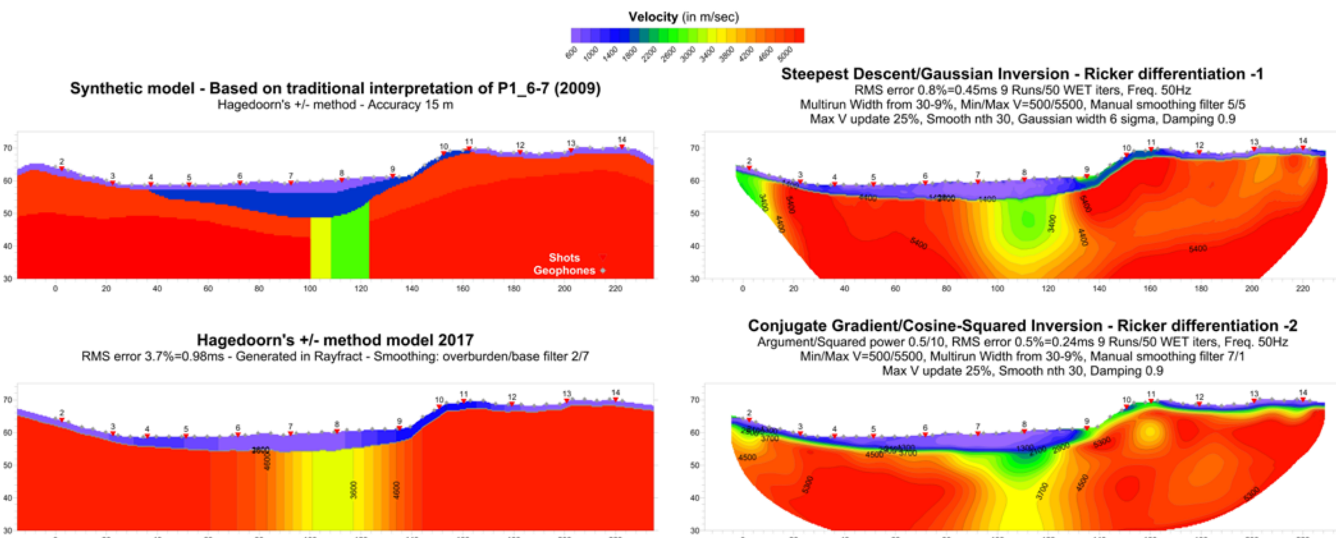

Figure 1: Left - Synthetic data based on traditional interpretation of Profile P1_6-7 from Knappe (top) and automatically calculated Plus-Minus model (bottom). Right - Inversion results using two different schemes.

Modeling Outline & Results

Our modeling efforts investigates several different inversion aspects as well as a variety of structures that are most likely to occur in Norwegian landscapes. Focusing on the structures included in our models, we attempted to vary the properties of each participant layer or zone according to the experience that the NGU had gathered from prior refraction seismic studies and resistivity modeling (Reiser et al., 2010). The cases examined cover various fracture zone velocities (1500 to 4500 m/s), fracture zone widths (5 to 40 m), fracture zone depths (5 to 40 m), fracture zone inclinations (15 to 60^{o}), overburden thicknesses (5 to 20m) and a few combinations between these variations (Tassis et al., 2017). Modeling builds up from the simplest case to models which simulate real conditions as good as possible without the addition of any type of noise. In our case, the simplest scenario amounts to a single fracture zone surrounded by homogeneous bedrock without any overburden. Synthetic data were then produced with geophone spacing equal to five meters (24 geophones in total per profile) and the ideal shot spacing according to inversion requirements (15 meters). The most complex scenarios that we have devised for this study, are profiles based on the traditional seismic interpretations obtained from the Knappe tunnel data and they portray probable soil layers of various thicknesses covering bedrock and fractures alike as well as multiple possible weakness zones (**Figure 1** and **2**). The models based on the real data from Knappe used the actual field recording settings (4 times the geophone spacing - not ideal but sufficient for inversion).

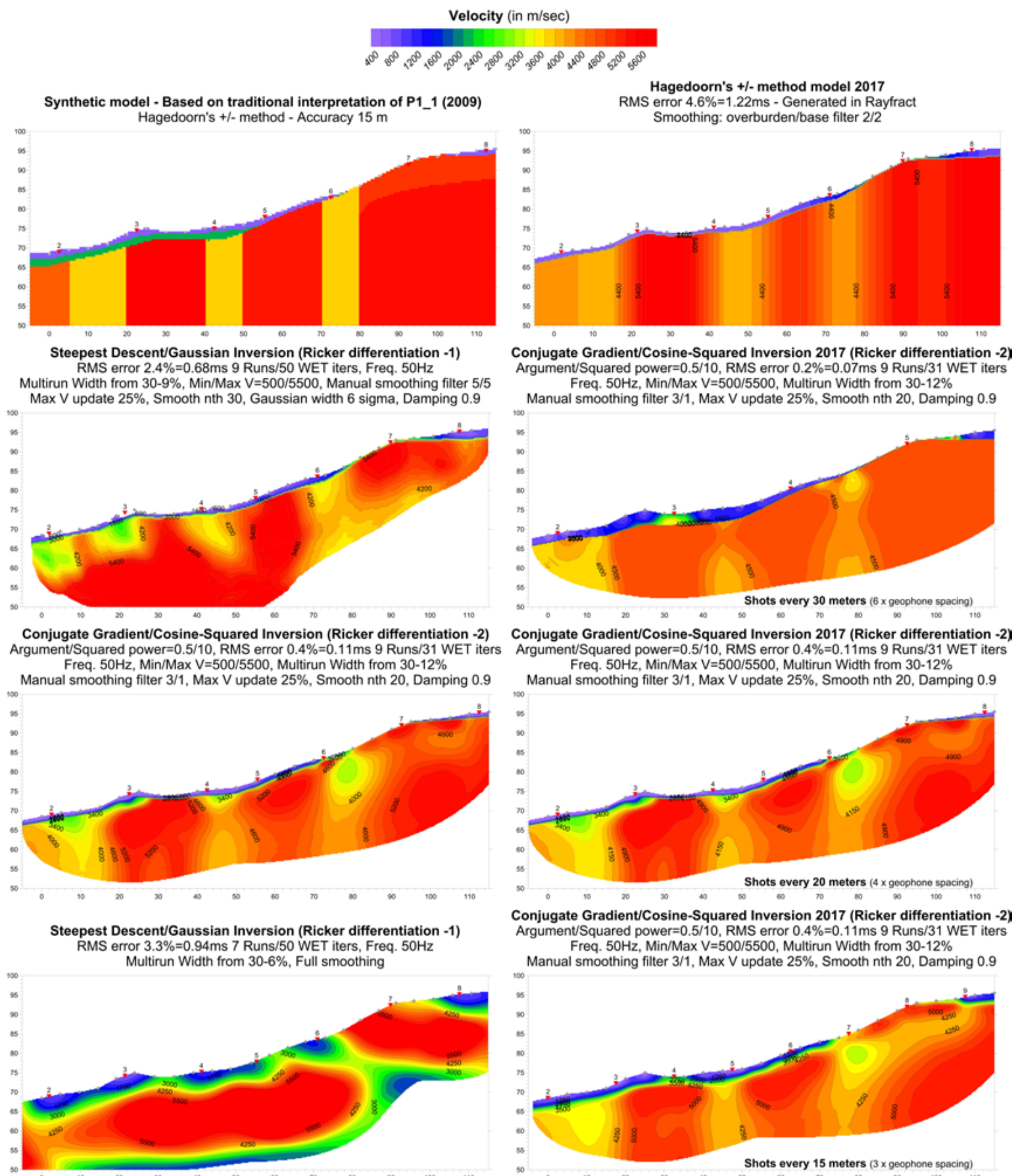

Figure 2: Left - three inversion approaches on synthetic data based on traditional interpretation of Profile P1_1 from Knappe. Right - effect of shot-distance on inversion results using the optimal scheme.

Results shown in **figures 1** and **2** indicate that when the Conjugate Gradient/Cosine-squared inversion scheme is used, fracture zones are detectable in all cases with the only real challenge being continuation with depth which is of course limited by the geophone spacing used. Position and width are accurate whereas the fracture velocity varies and can be underestimated in value. Overburden layers do not hinder the detection of weak zones but layering within them is limited by the software to two, and are detectable only when sufficient density of shots is applied (not possible in the case shown in **figure 1**). Furthermore, adjacent zones are not possible to differentiate and instead appear as one merged zone with a velocity representative for both modeled zones (**Figure 1**). Artefacts more commonly appear on the edges of the profiles and therefore, zones interpreted in such areas are doubtful.

Discussion - Conclusions

First and foremost, this modeling procedure has proven that refraction seismic tomographic inversion can be used to detect and characterize fracture zones in bedrock and Rayfract® is a software adequate to see this task through. It provides a large range of procedures-parameters and offers a variety of approaches when trying to locate the position and attributes of a weak zone. It is also a program that is constantly updated with newer and more powerful tools. It is therefore self-evident that it requires a skilled person to perform a reliable inversion. In this sense, a set of so-called "conservative" inversion schemes was compiled whose effect on known structures was documented and analyzed. Generally, if vertical zones are indeed present in the underground, tomographic inversion can locate them even at the stage of manufacturing an initial model within Rayfract® by using Hagedoorn's Plus-Minus method.

More specifically, we obtained the best results by using multi-run inversion instead of single-run, with decreasing width of variable intensity and by using default frequency (50 Hz) and a variable number of iterations in connection with the mathematical error of the inversion result. Moreover, the best inversion scheme consisted of multi-run Conjugate Gradient search method combined with Cosine-Squared weighting and minimal smoothing. This combination was validated in the reprocessing of Knappe tunnel data, when Steepest Descent/Gaussian weighted failed to give equally good results. This small scale reprocessing - whose traditional interpretation offered the basis for our two complex models - returned results which appear to be more sophisticated than the ones presented in Rønning et al. (2016), and they match the data collected after the construction of the tunnel better (ongoing work).

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