P-05-179

Oskarshamn site investigation

Re-interpretation of the refraction seismic profiles 277, 280 and 506 by use of Wavepath Eikonal Traveltime Tomography

A comparison with the traditional interpretation technique

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ISSN 1651-4416
SKB P-05-179

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Keywords: Refraction seismics, Deformation zone, Tomography, Overburden thickness, Velocity distribution, Mechanical properties

Abstract

The traditional technique for processing and interpretation of refraction seismic data is performed with pen and paper. The resulting geological models often display a deformation zone as a thin sharp low velocity zone surrounded by fresh rock. The real case is much more complex with different types of zones e.g. brittle, brittle-plastic, plastic-brittle and purely plastic types of deformation. The rocks surrounding a deformation zone may have reduced mechanical properties.

This document reports the results from re-processing and re-interpretation of existing refraction seismic data from the profiles 277, 280 and 506 in the Laxemar area. The data were processed by the use of the software Rayfract™, which by use of ray path estimations and inversion technique (WET or Wavepath Eikonal Traveltime tomography processing), creates a two dimensional velocity model in the ground beneath the measured profiles. The inversion models were compared to the existing velocity models gained from the traditional processing technique. The major aim is to test if it is possible by modern technique to extract more information from the refraction seismic data regarding velocity variations across deformation zones as well as variations in the unaltered rocks between the zones.

The investigation shows that the two different processing techniques result in velocity models that are comparable with each other. Information on soil cover thickness and the velocity distribution in the soil cover are similar. However, there is a clear indication that the WET-inversion models give more detailed information than the traditional models. The soil-rock boundary shows more complex variations and seems to be better resolved in the WET-models compared to the smooth variations in the traditional models. Both techniques identify possible deformation zones at similar locations, but the WET-models indicate a higher degree of complexity regarding velocity distribution and thus mechanical property variations within and in the vicinity of the zones. The WET-models also indicate that the sound rock displays velocity variations, whereas the traditional models indicate a constant velocity in the rock along the same section. The WET-model data are smoother and show less high frequency variations compared to the raw data, which indicates that the velocity variations are not the result of spurious travel time anomalies at single geophone stations.

In summary this investigation shows that, if the data coverage is good, by using modern inversion technique it is possible to present significantly more information about the seismic velocity distribution with depth from refraction seismic data than what is now being obtained by current processing techniques. Another strength of the WET-inversion technique is the direct possibility of quality control of the achieved velocity models performed by comparison of how well the model data fit the measured data and also by the evaluation of ray coverage plots. Therefore we suggest that previously measured refraction seismic profiles with a sufficient number of shot points should be re-interpreted by use of WET-tomography processing. Future profiles should from the start be interpreted by use of WET-tomography processing.

Sammanfattning

Det traditionella sättet att tolka refraktionsseismiska data utförs för hand med penna och papper. Resultatet av denna tolkning utgörs av en geologisk modell där t.ex. en deformationszon ofta är ett begränsat område med låg seismisk hastighet omgivet av homogent och bra berg. Verkligheten är mer komplicerad med olika typer av deformation såsom spröd, spröd-plastisk, plastisk-spröd och rent plastisk. Området närmast en deformationszon kan dessutom ha nedsatta mekaniska egenskaper.

Föreliggande rapport presenterar omprocessering och omtolkning av existerande refraktionsseismiska data från profilerna 277, 280 och 506 i Laxemar. Data processerades med programmet Rayfract™ som med hjälp av inversionsteknik (WET eller s k Wavepath Eikonal Traveltime tomography processing) beräknar en tvådimensionell hastighetsmodell i marken under den uppmätta profilen. De erhållna inversionsmodellerna jämfördes sedan med motsvarande modeller framtagna med den traditionella processeringstekniken. Målet med undersökningen är att testa om det med hjälp av modern teknik är möjligt att extrahera mer information från refraktionsseismiska data än vad som är fallet med nuvarande metoder.

Generellt sett är det en god överensstämmelse mellan de hastighetsmodeller som erhålls från tomografisk inversion och med traditionell teknik, främst med avseende på jorddjup, hastighetsvariationer i jordlagerföljden samt medelhastigheten i bra berg. Upplösningen nära ytan verkar dock vara bättre hos inversionsmodellerna och dessa modeller visar även hur hastigheten varierar inom själva bergvolymen. Båda processeringsmetoder indikerar låghastighetszoner på ungefär samma ställen men WET-modellerna indikerar en mer komplex hastighetsfördelning både inom och utanför zonkärnan. Dessutom indikerar tomografimodellerna tydliga hastighetsvariationer i partier med bra berg där den traditionella modellen indikerar en konstant hastighet.

Tomografimodellen är väl anpassad till uppmätta data och modellens 1:a ankomsttider uppvisar mjukare variationer än rådata vilket visar att de hastighetsvariationer i t.ex. bra berg som ses i modellerna knappast härrör från enstaka spridda anomalier.

Sammanfattningsvis visar denna undersökning att, förutsatt ett tillräckligt dataunderlag, är det möjligt att med hjälp av inversionsteknik ta fram mer information om hastighetsfördelningen mot djupet baserad på refraktionsseismiska data än vad som nu erhålls med dagens teknik. En viktig styrka med WET-tekniken är dessutom möjligheten till direkt grafisk och numerisk kvalitetskontroll av beräknade modeller. Vi föreslår därför att tidigare mätta profiler bör omtolkas med WET-processering förutsatt att dessa har mätts med tillräckligt många skottpunkter. Framtida refraktionsseismiska mätningar bör från start tolkas med denna metod.

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1 Introduction

The traditional technique for processing and interpretation of refraction seismic data is performed with pen and paper often displaying a deformation zone as a thin sharp low velocity zone surrounded by fresh rock. The real case is most likely much more complex. Deformation zones may have a narrow core of heavily crushed rocks, but they are often surrounded by a wider zone (influence area) constituting altered rocks with deteriorated mechanical properties as compared to the fresh rock.

This investigation aims at testing if, by use of modern computerized tools for analysing refraction seismic data (tomography inversion), it is possible to extract more information from the seismic data as compared to the traditional processing technique. If so, we will be able to create more advanced geological models that come closer to the complex reality.

This document reports the results from re-processing and re-interpretation of refraction seismic data of the profiles 277, 280 and 506 in the Laxemar area (Figure 1-1). The data acquisition and original interpretations have previously been presented by Gustaf Lindqvist (MRM Konsult AB) in the reports SKB P-04-134 and SKB P-04-298 /1, 2/. The refraction seismic measurements are one of the activities performed within the site investigation at Oskarshamn.

The re-processing and re-interpretation was carried out in accordance with activity plan AP PS 400-05-032. In Table 1-1 controlling documents for performing this activity are listed. Both activity plan and method descriptions are SKB's internal controlling documents.

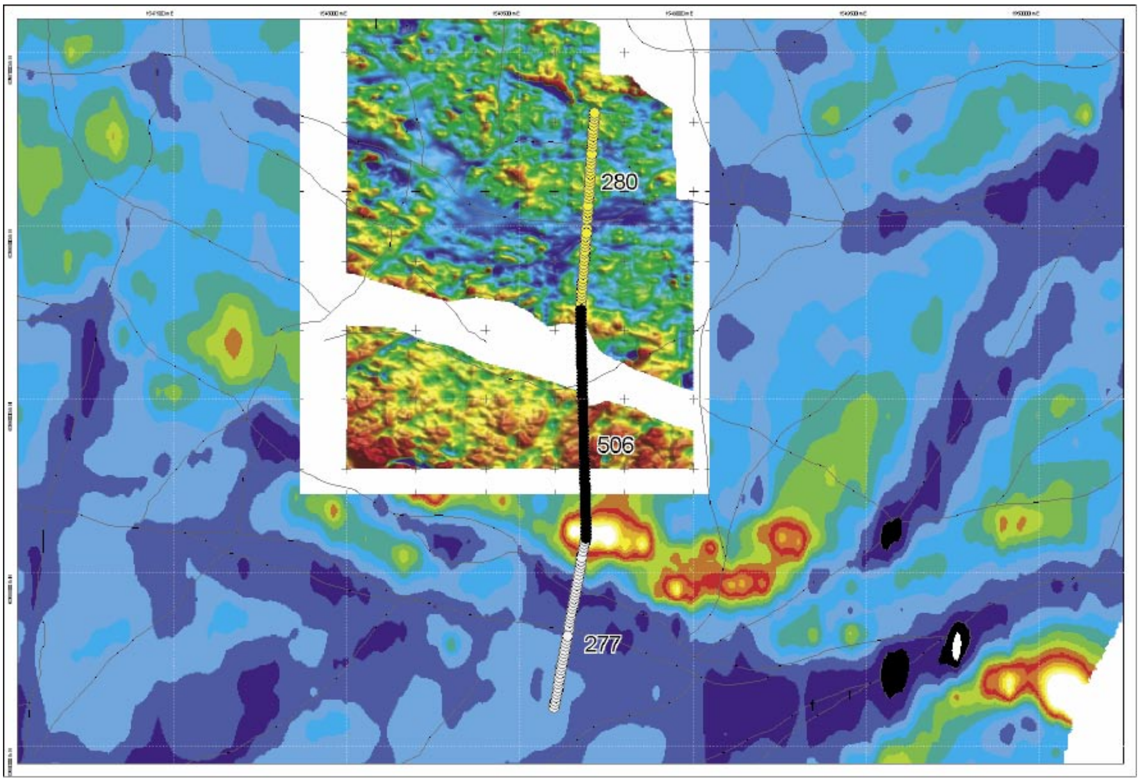


Figure 1-1. *The location of the refraction seismic profiles 277, 280 and 506 lying on top of a map showing lineaments (black lines) and combined helicopter borne and ground magnetic total field data.*

Table 1-1. Controlling documents for the performance of the activity.

Activity plan	Number	Version
Tolkning av refraktionsseismiska data från Laxemar med hjälp av semiautomatisk mjukvara	AP PS 400-05-032	1.0
Method descriptions	**Number**	**Version**
Metodbeskrivning för refraktionsseismik	SKB MD 242.001	1.0

The delivered raw and processed data have been inserted in the database of SKB (SICADA) and data are traceable by the activity plan number.

2 Objective and scope

The scope of this project is to use the software Rayfract™ version 2.61 (intelligent Resources Inc.) to re-interpret the refraction seismic profiles 277, 280 and 506 by use of tomography inversion technique, see e.g. Schuster and Quintus-Bosz (1993) /3/, and to compare the resulting geological models with those previously presented for the three profiles achieved from traditional interpretation techniques /1, 2/. The traditional models often indicate sharp zones of "bad or crushed rock" surrounded by large volumes of "good rock". The major aim of this project is to test if it is possible by modern technique to extract a more diverse bedrock velocity model which probably is to be expected in areas where both brittle and ductile deformations have interacted.

3 Equipment

3.1 Description of interpretation tools – Rayfract ™

The softtware Rayfract™ is a Windows based 32-bits software package for processing of refraction seismic data (www.rayfract.com). The program basically offers three different ways of processing the data.

1. Traditional processing by the methods “CMP intercept time refraction”, “Plus-Minus” and “Wavefront” (reminds of the techniques now often used in Sweden, see e.g. Sjögren (1984) /4/)
2. Delta-t-V-method, Gebrande and Miller (1985) /5/. It is a pseudo 2D inversion method that delivers a continuous 1D velocity versus depth model for all geophone stations. Alternatively a 1D velocity gradient model for smooth inversion can also be calculated.
3. WET or Wavepath Eikonal Traveltime tomography processing. Wave propagation is modelled in a physically meaningful way with ray paths, using the output from the Delta-t-V or velocity gradient inversion as starting model. It handles several real life geological situations, such as discontinues velocity distribution and sharp vertical or horizontal velocity gradients caused by e.g. deformation zones. Quality control of geological models is performed by direct graphical comparison of the measured travel-time data to those calculated from the model solution. The ray coverage with depth along the profile is displayed in a contour plot, which gives information on the reliability of the velocity model.

4 Execution

4.1 Preparations and data handling

Since one of the aims of the project was to compare the velocity models from traditional processing technique with tomography inversion technique, it was important that the input raw data (1st arrival times and station co-ordinates) for the tomography inversion was identical to the data used in the traditional processing.

Data protocols and seismograms with the 1st arrival time picks marked are only stored as paper copies (note, travel time data are not saved digitally). Excel spread sheets with columns for all necessary information (coordinates, arrival times, elevation, shot depth, correction factors etc) were created and filled with data digitized from the paper seismograms. In all more than 2000 arrival times from 86 shots were digitized for the three profiles 277, 280 and 506.

4.2 Data processing

Data processing with Rayfract™ is fairly simple and straight forward. Once the raw data were digitized, the Excel spread sheets were exported to ASCII-files, which were directly imported to the software.

The travel time curves are viewed in a time-distance graph, and each curve (one for every shot) was compared to the original time-distance graphs from the original investigations, and if necessary data were corrected.

Different ways of processing were tested on parts of the data (different starting models, various filter lengths and degrees of smoothing), in order to find the most appropriate technique for each of the three profiles.

The three profiles 277, 280 and 506 were processed separately in their full length. The number of shots and receiver stations is presented in Table 4-1 below.

Table 4-1. Number of shots and receiver stations for the refraction seismic profiles 277, 280 and 506.

Profile number	Number of shots	Number of receiver stations
277	20	100
280	22	114
506	44	133

In order to achieve reliable velocity models with the WET tomography inversion the software requires an estimated minimum of 10 shots/profile (though 5–7 shots should be sufficient according to numerous tests quoted in the manual), and also that the different receiver spreads overlap by a few positions. These criteria are only fulfilled for profile 506, which has twice the number of shots compared to 277 and 280, and 506 also has two stations overlap for each spread. The profiles 277 and 280 have gaps between the different spreads and relatively few shots, which means that the estimated velocity models for these two profiles clearly are more uncertain than for 506.

In general the processing sequence began by creating a 1D starting model and then performing 10–25 iterations of WET tomography. The modelled travel time curves were compared to the raw data curves, and if the result was satisfactory (if the fit was considered good) the velocity model was saved; otherwise more iterations were performed. Apart from the visual inspection of the travel time curves, the software also automatically reports the time residuals for the best fitting (minimum error), worst fitting (maximum error) model travel time, and also the mean error.

The profiles 277 and 280 were processed by a velocity gradient starting model followed by smooth WET tomography inversion. This type of processing gives a smooth velocity distribution with low near surface resolution and a decreased influence from minor anomalies or sharp velocity contrasts. The reason for calculating a smooth velocity model is the bad data coverage for these two profiles.

Processing of profile 506 began by creating a starting model with the delta-t-V method, and than performing 25 iterations of WET tomography with low smoothing. This processing technique gives high near surface resolution and also takes into account sharp velocity gradients.

The velocity models are presented as coloured contour plots (maps) showing the velocity distribution versus depth along the profile. Contour plots displaying the ray coverage versus depth along the profile were also created in order to better evaluate the reliability of the models.

4.3 Nonconformities

No nonconformities are reported.

5 Results

5.1 Profile 277

The resulting WET tomography inversion velocity model is presented in Figure 5-1 (top) as a colored contour map and the corresponding model based on the traditional processing technique is shown in Figure 5-1 (bottom). The colors (velocities) in the contour map roughly correspond to the following geological features:

Blue (400–1,700 m/s)	= soil or extremely crushed rock
Green (1,700–3,500 m/s)	= solid moraine or fractured rock
Yellow (3,500–4,200 m/s)	= fractured/weathered/altered rock (indicating soil-rock boundary)
Red-white (4,200–6,200 m/s)	= sound rock

The data coverage is fair along major parts of the profile but there are only two shots covering the section c 340 m to 390 m, which reduces the reliability of both models along this section presented in Figure 5-1. There is also a complete data gap in the section 125–135 m caused by a road crossing.

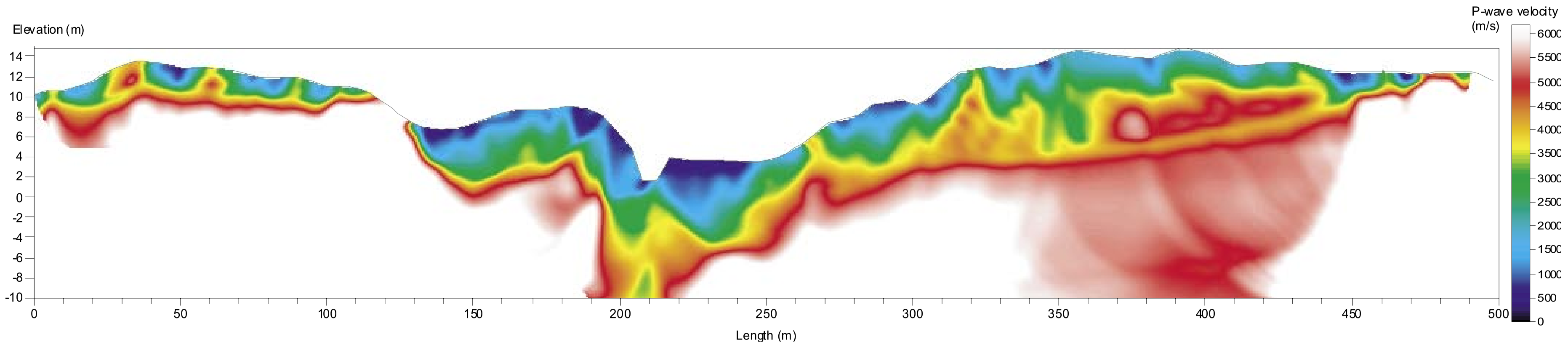
There is a general agreement between the WET model and the traditional model. The first 130 m of the profile are dominated by a thin soil cover (or no soil cover) and rock velocities of 5,500–6,000 m/s. At c 130 m the soil cover thickness increases to 4–5 m, and this increase coincides with a slight topographic depression at 130–150 m. The rock velocity appears to be fairly constant in the section 100–190 m, however, there is partly bad data coverage and the ray coverage in the WET model is low. At c 190 m section length there is a sharp bedrock topographic depression, and there is also a significant decrease in the rock velocity in both models. However, note that in the traditional model there is only a narrow zone of low velocity indicated, whereas in the WET tomography model the low velocity zone, which seems to be dipping slightly towards north, is surrounded by an influence area of 25–30 m width, and it is also possible to identify velocity variations within the indicated deformation zone.

Beyond 270 m there are significant differences between the traditional model which indicates fairly constant velocities of 5,300–5,700 m/s, when the WET tomography model indicates a much more complex velocity distribution. According to the latter model the bedrock surface is rough and soil or crushed rocks cover the uppermost c 4–5 m. A major depression in the bedrock surface is indicated at 340–360 m. As mentioned above it is important to note that the data coverage is low at 340–390 m, which reduces the reliability of both models, however the rock velocity is most likely better determined in the traditional model since the WET-model is badly constrained and “ to low data coverage warnings” are announced by the Rayfract software.

Along the last 50 m of the profile there is a good agreement between the two models.

PROFILE 277

Tomography inversion model



Traditional refraction seismic model

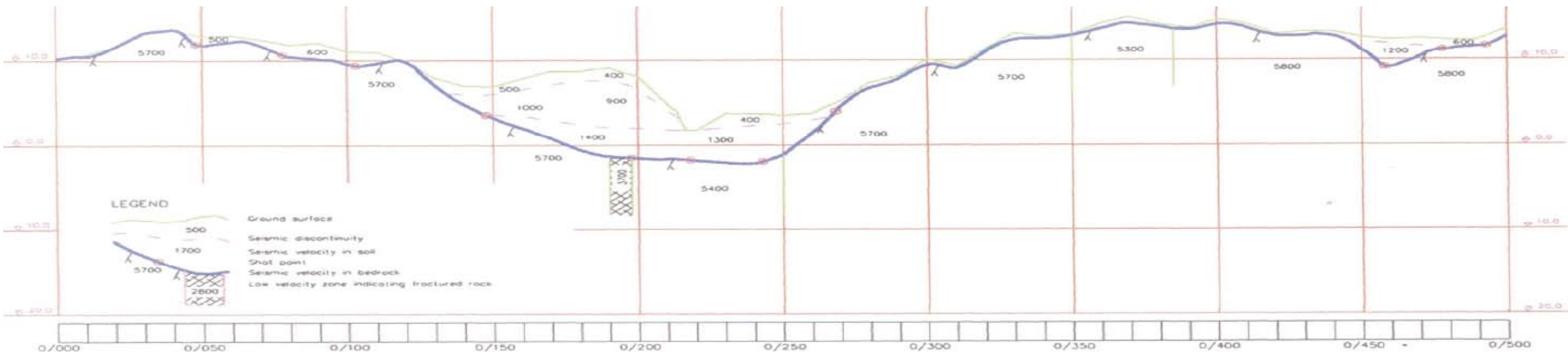


__Figure 5-1.__ Profile LSM000277. Upper part displays a contour plot of the velocity distribution in the WET tomography model. Lower part displays the velocity distribution based on traditional processing technique.

5.2 Profile 280

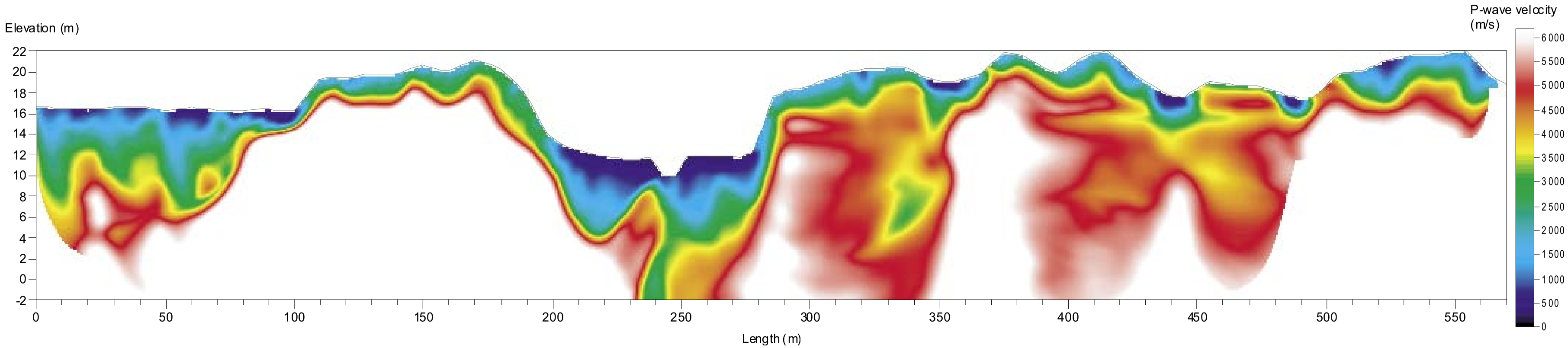
The resulting WET tomography inversion velocity model is presented in Figure 5-2 (top) as a colored contour map and the corresponding model based on the traditional processing technique is shown in Figure 5-2 (bottom).

As for the profile 277 there is a general agreement between the velocity model based on the traditional processing technique and the WET tomography model. The first 100 m are characterized by a flat topography profile and a soil cover thickness of 5–8 m in both models. However, the indicated bedrock surface seems to be fairly rough in the WET tomography model and shows a large number of topographical variations as compared to the traditional model. This is interesting information since the WET tomography modeling is performed with a high degree of smoothing. Between 100 m and 200 m there is a topographic high, with no or very little soil cover indicated in both models. The estimated rock velocities in the first 200 m of the profile are high and fairly constant. At 200 m to 280 m the profile crosscuts a major topographic depression in which the soil cover is fairly constant at about 6 m in the traditional model and varies in the range of 2–6 m in the WET tomography model. In the WET tomography model a low velocity zone is indicated at c 230–245 m with an influence area at 245–260 m, with an indicated dip towards south. In the traditional model two adjacent zones are indicated at c 260–285 m, with a location roughly further 15 m to the north. A comparison of the measured and WET-modeled travel time data shows that there is a bad model fit at the section coordinate 245 m, which might affect the location of the low velocity zone and partly explain the differences between the two models. However, along the section 250–285 m there is a good correlation between the WET-modeled and the measured travel times, which supports the result of the WET tomography modeling. After passing the topographic depression the soil cover almost disappears completely in the traditional model and seems to be 1–2 m in the WET model. This indicated soil cover in the WET model is most likely caused by the velocity gradient starting model and the smooth inversion technique, which decreases the near surface resolution. At 340–360 m there is a minor topographic depression that seems to be filled by soil, and both models indicate a low velocity zone in the bedrock. However, the WET tomography model indicates a variable zone width of about 0–20 m possibly indicating a dip towards south, whereas the traditional model indicates a sharp and narrow zone of about 5 m width, located approximately 10 m to north compared to the WET tomography model.

Comparing the two models as a whole there is a general agreement, but it is clear that the WET tomography model indicates a rougher bedrock surface and also seems to overestimate the soil cover thickness. However, the latter is a result of the smooth processing technique used because of the low data coverage.

PROFILE 280

Tomography inversion model



Traditional refraction seismic model

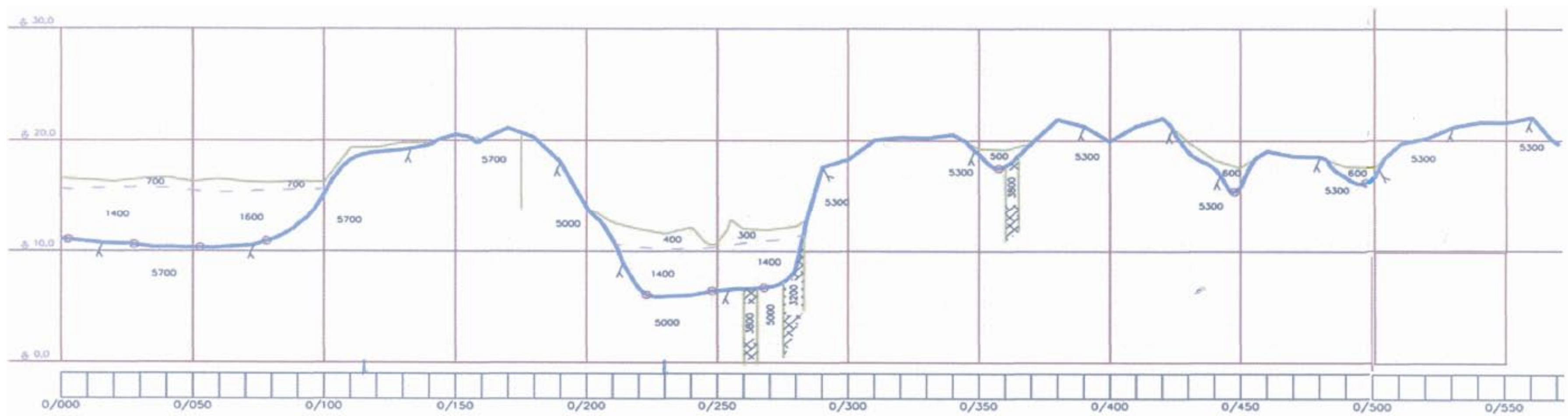


Figure 5-2. *Profile LSM000280. Upper part displays a contour plot of the velocity distribution in the WET tomography model. Lower part displays the velocity distribution based on traditional processing technique.*

5.3 Profile 506

The resulting WET tomography inversion velocity model is presented in Figure 5-3 (top) as a colored contour map and the corresponding model based on the traditional processing technique is shown in Figure 5-3 (bottom).

The profile 506 is the only one of the three investigated profiles that actually fulfills the requirements of the Rayfract software regarding the number of shots and overlapping spreads. The ray coverage is displayed in Figure 5-4a.

The comparison between the traditional and the WET tomography models shows (in the same way as for profiles 277 and 280) a general good agreement regarding soil cover thickness and velocity distribution within the soil cover. In both models there is a clear indication of two soil layers; an upper layer with velocities of 400–800 m/s and a lower layer with velocities in the range of 1,000–1,700 m/s.

However, there are major differences between the two models when looking at the velocity distribution in the bedrock. The traditional model indicates an almost constant rock velocity of 5,600 m/s along the entire profile. The few exceptions are three narrow (only 5–10 m wide) low velocity zones and a slight decrease in the rock velocity down to 5,000 m/s in the section 550–600 m.

The WET tomography model indicates a more complex velocity distribution along the profile. In the section 120–230 m there is a general decrease in the seismic velocity, indicating an inhomogeneous distribution with velocities in the range of 3,500 m/s to 6,000 m/s, and two possible deformation zones at c 140 m and 220 m. The latter coincides with a zone indicated in the traditional model. A control of the WET-modeled travel times with the actual measured travel times shows a fairly good model fit. The WET-model data are smoother than the measured data, showing less high frequency variations, which indicates that the velocity variations in the section 140–220 m are not the result of spurious travel time anomalies at single geophone stations. The ray coverage (Figure 5-4) is very good along the entire profile.

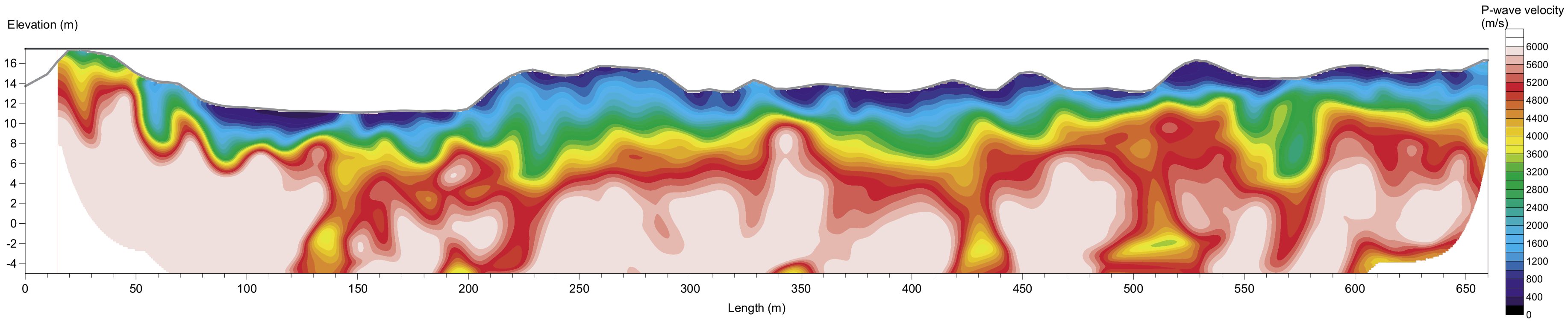
At 410–440 m both models indicate the presence of a low velocity zone in the bedrock, which is more distinct (width of c 5 m) in the traditional model compared to that of the WET tomography model (width of c 10–20 m). The WET tomography model show a location of the zone centered about 10 m further to the north,

The low velocity anomaly at 500–520 m length (elevation c –2 m) seems a bit unnatural, and the ray coverage is very low at this depth which indicates that the anomaly might be an artifact.

In the section 545 m to 585 m there is a significant depression of the bedrock surface, or possibly a major low velocity zone (v = 3,200 m/s) of perhaps weathered or altered rocks, indicated in the WET tomography model. This section coincides with a slight decrease in the rock velocity indicated in the traditional model.The WET-modeled travel times fit fairly well to the measured data.PROFILE 506

PROFILE 506

Tomography inversion model



Traditional refraction seismic model

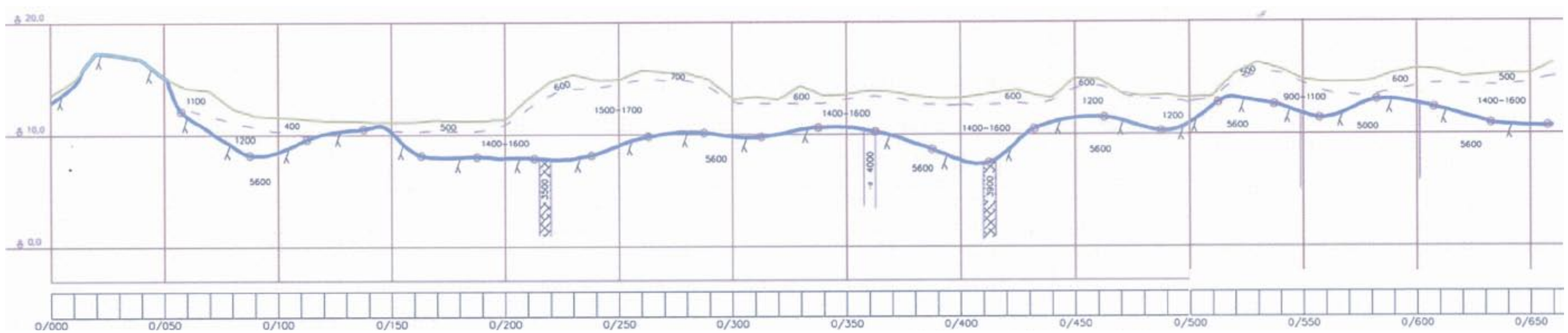
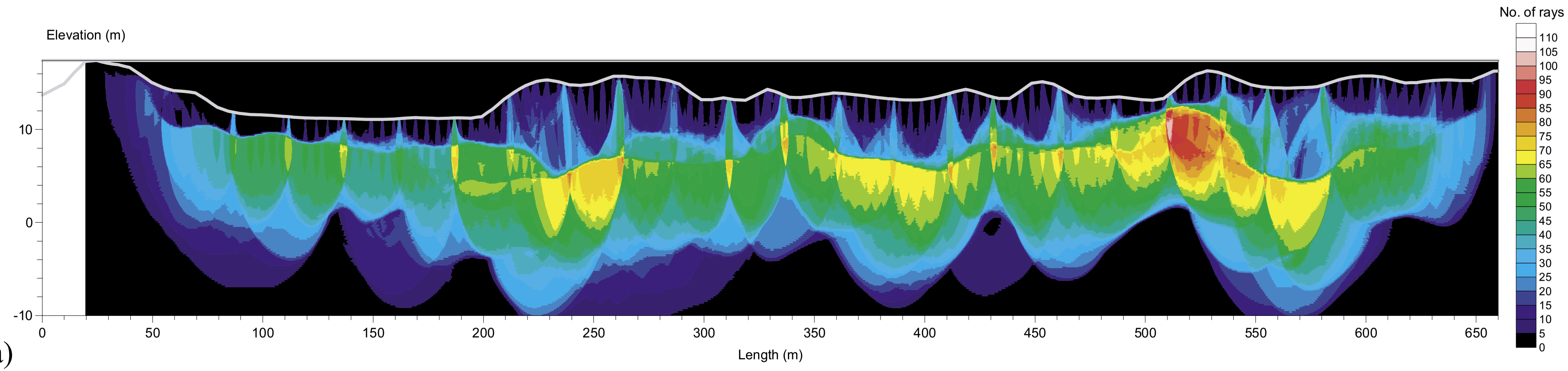
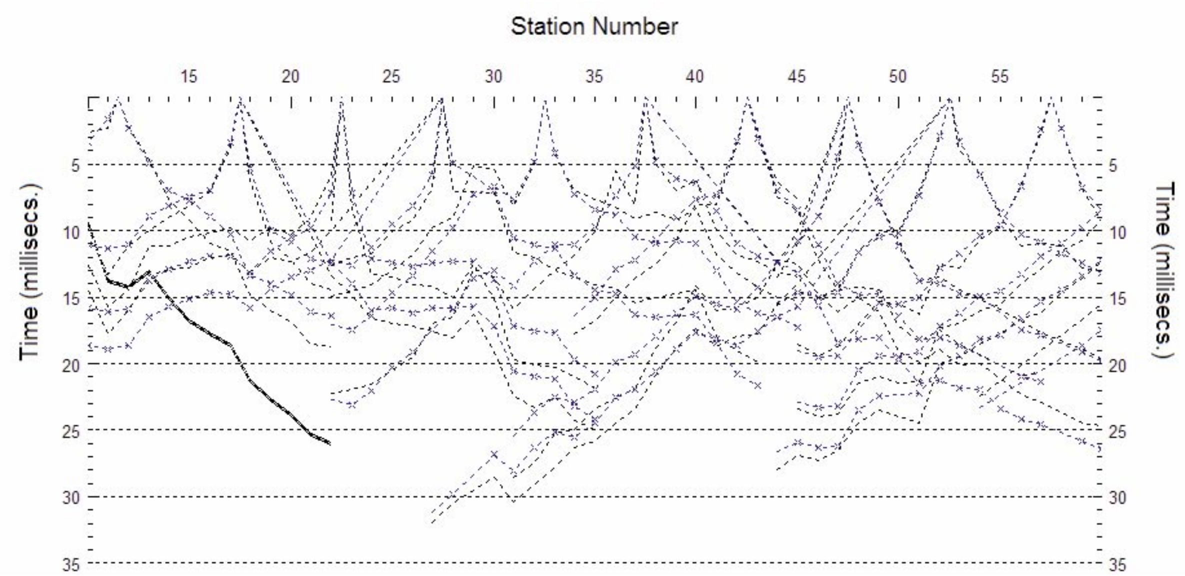


Figure 5-3. *Profile LSM000506. Upper part displays a contour plot of the velocity distribution in the WET tomography model. Lower part displays the velocity distribution based on traditional processing technique.*

PROFILE 506



a)



b)

Figure 5-4. *a) Contour plot of the ray coverage in the WET tomography model of profile LSM000506. b) Travel time curves for part of profile LSM000506. Hatched line indicates raw data and hatched line with crosses indicates model data.*

6 Summary and discussions

In this investigation two different techniques for processing refraction seismic data are compared. The traditional technique, predominantly used in Sweden today (e.g. Sjögren, 1984 /4/), is performed by use of pen and paper, basically by identifying linear segments in the time-distance graphs that are transformed to velocities. The other technique is so called tomography inversion, which is a computer based way of numerically estimating a best fitting velocity model to the measured data.

The tomography inversion was performed with the software Rayfract™. The program uses so called WET or Wavepath Eikonal Traveltime tomography processing. Wave propagation is modelled in a physically meaningful way with ray paths. It handles several real life geological situations, such as discontinues velocity distribution and sharp vertical or horizontal velocity gradients caused by e.g. deformation zones. Quality control of geological models is performed by direct graphical comparison of the measured travel-time data to those calculated from the model solution (Figure 5-4b). The ray coverage with depth along the profile is displayed in a contour plot, which gives information on the reliability of the velocity model (Figure 5-4a).

This investigation shows that the two different processing techniques result in velocity models that are comparable with each other. Information on soil cover thickness and the velocity distribution in the soil cover are similar. However, there is a clear indication that the WET-inversion models give more detailed information than the traditional models. The soil-rock boundary shows more complex variations and seems to be better resolved in the WET-models compared to the smooth variations in the traditional models. Both techniques identify possible deformation zones at similar locations, but the WET-models indicate a higher degree of complexity regarding velocity distribution and thus mechanical property variations in the vicinity of the zones. The WET-models indicate that also the sound rock displays velocity variations, whereas the traditional models indicate a constant velocity in the rock along the same section. In the manual time-distance plot there is for the bedrock no indication of increasing sound velocity with depth. In Figure 5-4a it is seen that the program to invert the data uses a significant volume of the bedrock. Due to the limited number of shot points there is always a risk that variations in the mostly dry surface layer between the shots are moved downward in the model.

Profile 506 is the only profile with high data coverage and overlapping spreads. The inversion model data fit fairly well to the measured data. The WET tomography model indicates a more complex velocity distribution along the profile as compared to the traditional model. For example, in the section 120–230 m there is a well defined general decrease in the seismic velocity and an inhomogeneous velocity distribution with variations in the range of 3,500 m/s to 6,000 m/s, and two possible deformation zones at c 140 m and 220 m. The traditional model indicates constant rock velocity along this section apart from one narrow deformation zone at 220 m. The hand plotted time-distance graph shows some small variations (could be errors) in the picking of the arrival times. In manual interpretation these variations are “filtered” away by the interpreter, whereas the computer program uses all data. It seems as if the software is sensitive to noise in the data. However, the WET-model data are smoother and show less high frequency variations compared to the raw data, which agrees with the reasoning.

A major strength with the WET-inversion technique is the direct possibility of quality control of the achieved velocity models. This is performed by graphical viewing of how well the model data fit the measured data, and secondly by looking at the ray coverage plot that automatically comes with the model output. Numerical values of biggest, smallest and mean (RMS) error of the model time fit are also presented by the program.

In conclusion we suggest that some previously measured refraction seismic profiles crossing geological features of great interest should be re-interpreted by use of WET-tomography processing. The data coverage should according to the discussion above be good. Future profiles to be used for the method should be performed with overlapping spreads (2 or more geophone stations) and at least 7 shots per spread layout. The data should be moved directly from the instrument into the WET-tomography processing program.

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