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On the quantitative determination of coal seam thickness by means of In-Seam Seismic Surveys

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Abstract

By means of ISS surveys carried out at Karvina coal mine of OKD, Czech Republic in two neighbouring panels it is shown how the distribution of the coal seam thickness can be investigated if the coal seam consists of almost pure coal. The coal seam under investigation was considerably affected by erosion which resulted in thickness changes amounting from about 30 cm up to around 4.40 m. By applying ISS tomographic inversion to the group travel-times for a constant frequency value first the distribution of the related group velocity was determined which already showed the extension of the erosions within the survey areas. By correlating the group velocity distribution with known values of the coal seam thickness along a gate a relation in terms of a polynomial approximation between these quantities could be derived. This relation is specific for a chosen frequency value and resolves in general only some thickness range. For the application presented in this paper a value of 200 Hz was chosen for the constant frequency value by which a range of the coal seam thickness from about 100 cm to about 300 cm was resolved. This was also the main objective of the surveys. For the investigation of a greater variation of the coal seam thickness (or even the complete thickness distribution) the described procedure has to be repeated for different constant frequency values. The final thickness map has then to be combined from the individual results for the different constant frequency values.

The thickness range which had to be investigated by the surveys was in good agreement with the thickness encountered by mining the panel.

Key words: In-Seam Seismic (ISS), ISS wave, Love wave, coal seam thickness, wave guide, dispersion

1. Introduction

The mining at the coal mines of OKD in the Karvina Subbasin in the Czech Republic is often seriously affected by erosion (Waclawik 2011). As a consequence the thickness of the coal seam can considerably vary in eroded coal seam areas from small amount up to complete erosion. Because of technical and economical reason the knowledge about their location and the remaining coal seam thickness within the erosion areas is required prior to the mining of coal panels or even for its designs.

The in-seam seismic (ISS) survey technique (Buchanan and Jackson 1986; Dresen and Rüter 1994, Waclawik and Schott 2011) is able to locate such areas as it “looks” parallel to the layering. It uses the ability of coal seams to guide seismic waves. By applying transmission surveys disturbed and undisturbed coal seam areas can be separated and by applying the reflection method the borders of eroded areas or even erosion channels can be located in case of almost sudden thickness changes (Waclawik and Schott 2011). In addition by applying ISS-tomography (Schott and Brandt 2003) to the transmission data the coal seam structure and the remaining coal seam thickness can be investigated.

ISS-tomography is based on the dispersive property of the guided seismic waves which means that their propagation velocity depends on frequency. As a consequence an initial seismic pulse becomes a longer wave train with increasing distance from a seismic source along which the frequency does change corresponding to the dispersion law. For the propagation of dispersive waves the phase velocity and group velocity can be considered. Both are important properties of these waves. The phase velocity describes the change of the phase along the dispersive wave train with changing distance from a source while the group velocity determines the travel-times of the individual frequency portions. As the phase velocity is more difficult to extract from observed data ISS-tomography is currently solely applied to investigate the variation of the group velocity.

ISS-tomography is related to global surface wave tomography but in a much higher frequency range (Barmin et al. 2001). While global surface wave tomography uses frequencies considerably less than 1 Hz, the working frequency for ISS-tomography depends on coal seam thickness and ranges from about 100 Hz to more than 600 Hz.

The ISS waves recorded generally at ISS surveys are Love waves (SH waves). Therefore in any case the word ISS wave is used in the following then it refers to the Love wave.

The dispersion of the ISS waves is uniquely defined by the coal seam structure and the properties of the rock along roof and floor (Räder et al. 1985). The propagation velocities of the S-waves (body wave) and the densities within coal, rock and dirt bands (which again may have some coal content) and the thickness of the individual coal and dirt band layers are the essential quantities. Hence the coal seam structure can generally be investigated by analysing the dispersion of the recorded ISS waves.

In the case of interbedded strata of coal and dirt band layers (Fig. 1) a general inversion method has to be used (Dobroka 2005) for this purpose. At first ISS tomography has to be applied to the dispersion derived from the observed ISS waves (in general the group travel times). As multiple quantities (thickness, S-velocity and density within the individual coal and dirt band layers) have to be determined the tomographic inversion has to be applied for multiple frequencies or even for the complete frequency content of the observed ISS waves. This will result in a distribution of laterally varying dispersion curves of the group velocity (the phase velocity is currently not used as it is still difficult to extract it from the observed data). The cell size of the tomographic inversion grid should be sufficient small that the local coal seam structure within these cells can be considered as constant. Then the general inversion process can be applied to these local valid dispersion curves (which has to be verified) to derive a model of changing coal seam structure within a survey area.

Forward modelling is used to determine the dispersion of the ISS-waves for an initial model of the coal seam. Its result is compared to the observation and from the difference corrections for the initial coal seam model are derived. This procedure is repeated until the modelling result approaches the observation and the difference will at least be smaller than a specified threshold. This procedure has to be applied to every cell of the grid defined for the tomographic inversion and will therefore result in a huge computational effort.

But in almost pure coal seams without dirt bands this effort can be considerably simplified as the coal seam thickness is the dominant quantity which determines the dispersion. The S-velocities in coal and rock can be estimated directly from the observed dispersion curves as they approach these values

towards higher and lower frequencies. And the densities for rock and coal can be considered as known.

ISS-tomography is applied as follows: By means of the multiple filter technique (Dziewonski et al. 1969) the group travel-times of the ISS-waves for a constant frequency value are determined from every recorded data trace. The application of ISS-tomography yields the distribution of the group velocity within the survey area for the pre-given frequency value. This result already shows the locations of present anomalies which might be related to eroded coal seam areas. This procedure sounds simple. But the extraction of the group velocity from the data of the recorded ISS-waves propagating through present anomalies and the proper identification of the group travel-times is often difficult. Faults or greater topography changes (for instance synclines) will complicate this procedure especially if they are unknown. Finally also the number of data traces which have to be analysed and which may amount from several hundred to even several thousand depending on the size of the survey area and the presence of more complicated geology (known or unknown) determines the effort to receive the final input data set for the tomographic inversion process.

By means of two ISS surveys carried out in two neighbouring panels at Karvina coal mine of OKD in 2010 and 2011 it will be shown how the distribution of the coal seam thickness can be derived from ISS transmission data if the coal seam consists of almost pure coal. First ISS tomography was applied to the group travel times of the recorded ISS waves for a constant frequency value which results in a distribution of the group velocity within the survey areas. By correlating the group velocity with known values of the coal seam thickness along the gates yields a relation between coal seam thickness and the group velocity. The distribution of the coal seam thickness is then finally achieved by applying this relation to the distribution of the group velocity.

2. The survey area

The site map of the ISS surveys at Karvina coal mine (Fig. 2) shows the location of the two neighbouring panels 906 and 908. The extracted part of the panels is located at an average depth of 708 m. The layers of the 9th block generally dip 6° to the north-northeast (Jiránková 2012, Jiránková

2010). The realised survey areas (Survey Area 1 in panel 908 and Survey Areas 2A and 2B in panel 906) are shaded in grey. They are limited or splitted on request of the coal mine to reduce their general preparation effort for drilling the short boreholes needed for the surveys. These boreholes are used to place small amounts of explosives for seismic wave generation and for mounting the geophone probes to record the transmitted ISS waves. Every probe contains two geophones mounted perpendicular to each other within a rubber tube. By pumping air into the tube the probe is coupled pneumatically to the wall of the borehole and hence to the coal. The geophones within each probe are oriented parallel (X-component) and perpendicular (Y-component) to the adjacent gate within the seam plane. Therefore by one probe the complete vibration of the Love wave (SH wave) is recorded.

The geological sections along the gates 40907 and 40909 along panel 908 show a general coal seam thickness of around 4 m in this area interrupted by erosions in which the coal seam thickness does considerably vary and also locally decreases to less than 50 cm. These erosions were difficult or even impossible to mine. These surveys had the following objectives (remarks on their accessibility are added).

Survey Area 1 in panel 908: This survey should investigate the location of the eastern border of the erosion disclosed between the stations 180 m and 300 m along gate 40909 and the thickness variation within the east end of this panel. Further it should determine the extension of the erosion located between the stations 300 m and 400 m along gate 40907-1 into the panel 908 and the boundary line where the coal seam thickness may exceed 250 cm.

Originally it was planned to investigate the whole panel 908. But a final decision was made by the coal mine to restrict the survey area only to the east part of the panel. As a consequence the western border of the final survey area crosses a disclosed coal seam erosion. Further the gate 40990-3 was still under development and therefore not available for the survey. No transmission shots to and from this gate could be realised to collect additional information which were necessary for the application of ISS-tomography. These limitations had some consequences for the survey results. Limited accuracy had to be expected for the thickness distribution within the erosions along the western boundary of the survey area as well as within its east part. Finally the gate 40907-2 was already developed and would therefore act as an obstacle for the transmission survey. This gate interrupts the coal seam and can act

similar to a fault on ISS-wave propagation. To overcome this problem additional geophone stations were located within this gate.

Survey Areas 2A and 2B in panel 906: This survey should examine the extension of the eroded coal seam areas located along gate 40907-1 into the panel 906 and the boundary line where the coal seam thickness may exceed 250 cm.

As the transmitted ISS waves from the shots (ignition of the small explosives for seismic wave generation) within the Survey Area 2A were also recorded at the geophones located within the Survey Area 2B and vice versa ray paths were realised through the gap area. This enabled the application of tomographic inversion simultaneously to both areas 2A and 2B including the gap between them. But less accuracy had to be expected within this area especially closer to the gates because of the missing shots and hence missing information. Again the gate 40907-4 was already partly developed (the part perpendicular to gate 40907-1) into the Survey Area 2A. To overcome the problem with this obstacle, additional shot stations were located within this gate.

For all survey areas a distance of 20 m was selected between the shot and geophone positions. A map with the locations of all source and receiver stations is shown later in this paper. The gates 40909 for the Survey Area 1 and 40907-1 / 40907-3 for the Survey Areas 2A and 2B were chosen for the shot locations as these gates are more affected by erosion. The reason for that was that shots have a greater impact area while geophones measure seismic wave vibrations locally. Therefore geophones can be mounted more precisely where the coal seam is thicker.

3. Some theoretical background

For the forward modelling of the dispersion of the ISS wave (Love wave) in an almost pure coal seam a low velocity layer of constant thickness is considered which is embedded between two halfspaces. The halfspaces and the layer are referenced by the indices 1 (upper half space), 2 (embedded layer) and 3 (lower half space). The media (rock, coal) inside the halfspaces and the layer are considered to be homogeneous, elastic and isotropic. Then the propagation of a guided wave along

the layer is completely determined by the shear velocities β_i and the densities ρ_i in the media and the thickness h of the layer.

The Love wave is generated by interference of SH waves generated by source inside the layer which are multiple reflected at the interfaces towards the upper and lower half space. The phase recursion algorithm (Räder et al. 1985) leads to the following equation for the balance of the different phase shifts:

$$[1] \quad f(\omega, c, h) = \arctan\left(i \frac{\mu_1 \gamma_1}{\mu_2 \gamma_2}\right) + \arctan\left(i \frac{\mu_3 \gamma_3}{\mu_2 \gamma_2}\right) - \omega h \gamma_2$$

where $\omega = 2\pi\nu$ is the circular frequency (ν is the frequency),

c is the phase velocity of the ISS wave,

$\mu_i = \rho_i \beta_i^2$ is the modulus of rigidity,

$\gamma_i = \sqrt{\frac{1}{\beta_i^2} - \frac{1}{c^2}}$ is a propagation factor proportional to the vertical wave number,

i is the imaginary unit.

Construction by interference requires that the phase balance has to be 0 (fundamental mode) or $n\pi$ (for the higher modes). In the following only the fundamental mode is considered and it is assumed that the two half spaces contain almost identical media (symmetrical model). Then it follows from [1]:

$$[2] \quad 2 \arctan\left(i \frac{\mu_1 \gamma_1}{\mu_2 \gamma_2}\right) - \omega h \gamma_2 = 0$$

This equation has only a real solution for the phase velocity c if the following condition holds:

$$[3] \quad \beta_1 \geq c \geq \beta_2$$

For this condition γ_2 becomes real and γ_1 has to be taken as negative imaginary (square root of a negative number) which leads to an exponential decay of the amplitudes of the ISS wave away from the interfaces into the half spaces. Resolving [2] with respect to ω and h leads to

$$[4] \quad \omega = \frac{2}{h \gamma_2} \arctan\left(i \frac{\mu_1 \gamma_1}{\mu_2 \gamma_2}\right)$$

and

$$[5] \quad h = \frac{2}{\omega \gamma_2} \arctan\left(i \frac{\mu_1 \gamma_1}{\mu_2 \gamma_2}\right)$$

Equation [4] is the explicit solution for the phase velocity in terms of $\omega(c)$. For any given value of the phase velocity in the interval defined by [3] and a constant thickness value h results a value for the circular frequency ω . Equation [5] shows a similar dependency between the thickness h and the phase velocity for a constant frequency value. Equations [4] and [5] have a symmetric form in which ω and h are exchangeable. Hence the curve of [5] has a shape similar as the dispersion curve for the phase velocity.

Equation [5] shows the relation between the phase velocity c and the thickness h . But to derive the thickness distribution from a tomogram of the group velocity a relation between the group velocity u and the thickness h is required. The group velocity can be derived from the phase velocity as follows:

$$[6] \quad u = \frac{c}{1 - \frac{\omega}{c} \frac{dc}{d\omega}}$$

[6] applied to [4] yields the following dispersion equation of the group velocity:

$$[7] \quad u = c \frac{g(c) - \omega h}{g(c) - \omega h(1 + \gamma_2^2 c^2)} \quad \text{where} \quad g(c) = \frac{2i}{\gamma_1} \frac{\mu_1 \mu_2 (\gamma_2^2 - \gamma_1^2)}{\mu_2^2 \gamma_2^2 - \mu_1^2 \gamma_1^2}$$

This equation shows that the group velocity u depends also on the product ωh like the phase velocity c in equation [2]. This will result again in similar curves for $u(\omega)$ in which the thickness h is kept constant and $u(h)$ for a constant circular frequency ω . For the calculation of these curves equation [7] has to be used in combination with the equations [4] or [5]. It is also possible to replace the product ωh by using equation [2]. But the result will be a relation between u and c only. The information about their dependency on ω and h will be lost.

Fig. 3 shows the dispersion curves for the group velocity for different constant thickness values. The values for the shear velocities and densities are approximately valid for the Survey Areas 1 and 2. They are taken from the dispersion analysis results of ISS waves propagating through almost undisturbed coal seam areas. According to theory the observed dispersion curves should approach the

shear velocity in the surrounding rock towards lower frequencies and to the shear velocity in coal towards high frequencies and amounts approximately to 2450 m/s for β_1 and 1000 m/s for β_2 . For the densities 2.5 g/cm³ (siltstone / sandstone) and 1.3 g/cm³ (coal) are used.

The dispersion curves show a shape as it is known for a pure coal seam. Starting at the value for the shear velocity in the rock they show a steep descent within a smaller frequency range down to a minimum at a velocity less than the shear velocity in coal. Towards higher frequencies they approach the value for the shear velocity in coal from below. With decreasing thickness these curves are stretched towards higher frequency. This shape determines the appearance of the ISS waves in the seismogram. According to the steep descent of the group velocity in the dispersion curves a seismic pulse will become a longer wave train along which the frequency will increase. It will end with a wave packet (called Airy phase) with a frequency content and propagation velocity according to the values of the low velocity minimum.

By considering the frequency value of a low velocity minimum (for instance at curve (b)) it can be observed that the velocity does considerable increase as the coal seam thickness decreases. Fig. 4 shows this in more detail which shows the group velocity depending on seam thickness for different constant frequency values. The curves are displayed already according to the manner they are needed to determine a thickness distribution from a velocity tomogram. But their shape is similar as it can be seen for the frequency dependent group velocities in Fig. 3 according to the described theory.

In the velocity interval between about 1000 m/s and 2300 m/s a smaller thickness range is resolved. Below about 1000 m/s the relation between thickness and velocity becomes ambiguous and above about 2300 m/s the resolution decreases while approaching the shear velocity in the rock. Further every constant frequency value reacts on a different thickness range. From this comes up the idea to apply tomography to the recorded ISS waves at transmission surveys and to use the travel times at constant frequency values to detect and to locate thickness changes within coal panels. And if a relation between coal seam thickness and group velocity can be achieved by correlating it with disclosures even a thickness distribution should be possible.

4. The data and dispersion analysis

An example for the transmission data collected at the second survey in the northern panel is shown in Fig. 5. The data from all source stations S1 to S41 recorded at the receiver station G20 are displayed. By the two-component geophone probe the X-component (component parallel to the adjacent gate) and the Y-component (component perpendicular to the adjacent gate) the complete vibration of the ISS wave (Love wave) was recorded. The corresponding seismograms (for the X-component on the left side and for the Y-component on the right side) show clearly the dispersive signals of the ISS wave including the Airy phase which marks their end. The shift of the arrival time between the source stations S25 and S26 are caused by the gap between the two Survey Areas 2A and 2B. The source station S15 and S16 are located at the end of gate 40907-4 which was already developed into the Survey Area 2A.

From all data collected at the surveys in the two panels the travel times for a constant frequency value have to be determined. But first the constant frequency value itself had to be chosen.

By the survey the extension of erosions in the survey areas and the boundary line where the coal seam thickness may exceed 250 cm have to be investigated. From these requirements it followed that a thickness map had to be produced which show the locations where the coal seam thickness will become around 250 cm and smaller. Considering Fig. 3 the dispersion curve of the group velocity for a thickness of 250 cm will lie between the dispersion curves (c) and (d). The frequency value to be selected should lie left to the minimum of this curve that in case of smaller thickness than 250 cm higher velocities along the ascending part of the dispersion curve will affect the travel time. But in addition the frequency value to be selected should not be too far left of this minimum so that the velocity will not become too high. This will reduce the resolution. In this case a frequency value of 200 Hz was selected as the velocity for a thickness of 250 cm will amount to about 1000 m/s i.e. around the value for shear velocity in coal (Fig. 4).

Before starting with the picking of the travel times the coordinates of the source and receiver stations were assigned to the data. This enables to switch between the time, slowness or velocity domain during the picking procedure. To pick the values in the velocity domain enables further the

comparison between changing dispersion curves, to better follow velocity changes from one shot to the next shot and to verify if the picked value is realistic. This will be especially helpful in data with less signal-to-noise ratio.

Multiple filter analysis (Dziewonski et al. 1969) was applied to the data to resolve the time dependent frequency changes. Fig. 6 show the analysis results for the data of the three source stations S7 (left column), S21 (middle column) and S25 (right column) recorded at geophone station G20 displayed in the time domain (upper row), slowness domain (middle row) and velocity domain (lower row). The picked values are shown inside the individual displays. The analysis result for the source station S7 in the velocity domain resembles to a dispersion curve for a coal seam with almost constant thickness. Its minimum is located slightly shifted to lower frequencies compared to that of curve (c) for a 300 cm thick coal seam (Fig. 3). From this can already be concluded that between source station S7 and geophone station G20 the coal seam will be almost free of any erosion although S7 is located within the erosion disclosed along the east part of gate 40907-1. Hence this erosion will not have a greater extend into the direction towards G20 and the mean coal seam thickness between S7 and G20 will amount to greater than 300 cm. This means that already by inspecting the observed dispersion of the group velocity it is possible to distinguish between disturbed and undisturbed areas within the survey area of a coal panel.

The analysis result for the source station S25 in the velocity domain shows also a dispersion curve. But it has another shape compared to that from source station S7. No minimum is visible and the mean velocity is increased. From this observation one can conclude that the propagation of the ISS wave from S25 to G20 is already affected by erosion.

The analysis of the ISS wave from source station S21 shows a disturbed result. Only in the frequency range between about 150 Hz to about 300 Hz a part of the dispersion curve can be identified. The velocity value is increased by more than 25% compared to the result for source station S7. Here the conclusion is that the area between S21 and G20 will be strongly disturbed by erosion. This result shows that it is useful to pick the values in the velocity domain for the correct identification of valid dispersion curves.

Finally all picked velocity values have to be transferred into travel times by using the assigned coordinates.

5. Application of ISS tomography

For all combinations of source and receiver stations for which travel time values at the constant frequency of 200 Hz could be determined a ray coverage map was produced (Fig. 7). This map shows also the status of development of the gates as it was valid at the time for the second survey in the upper panel (Survey Areas 2A and 2B). Further it shows the location of all source and receiver stations.

The coverage map shows variable ray densities. Toward either side of each panel it become coarser as it was not possible to place source and receiver stations along gate 40990-3 in the East, along a connecting gate for the northern panel in the West (not visible in the maps) and by restricting the survey area in the southern panel to its east part. Within the gap between the Survey Areas 2A and 2B the ray density is high, but close to the gates no rays are visible because of the missing source and receiver stations. Also the influence of the gates developed into the survey areas (gates 40907-2 and 40709-4) is visible. By placing additional source and receiver stations within these gates it was tried to overcome their influence. But especially in the upper panel it was not really successful. The gate and the sudden change of the coal seam thickness west of it in combination was an unsurmountable obstacle.

The source station S50 in gate 40909-5 could not be realized because of drilling problems. An attempt was made to access there the coal seam below the gate. But it had finally no influence on the result.

But on the other side ISS waves were observed up to a distance of around 1000 m which resulted in an improvement of the ray density especially in the centre of the survey areas. But it is not really advisable to use them all without prior detailed examination. Because of refraction the ISS waves may propagate around smaller erosions and borders of erosions may become more diffuse. Or it can lead to

some contradiction if a good ISS transmissivity is observed even the presence of an anomaly or obstacle is known.

Here finally all picked travel times could be used for tomographic inversion. The simultaneous iterative reconstruction method (SIRT) was used combined with an averaging process between the iteration steps (Dines and Lytle 1979, Gersztenkorn and Scales 1988).

Fig. 8 shows the result in terms of the variation of the group velocity. This result already shows anomalies of higher group velocities which do correlate with the disclosed erosions along the gates and how far they do approximately extend into the panels. The erosions along the west part of gate 40907-1 and along its east part are restricted almost to the panel 908. This gate is just developed along their northern border. The panel 906 is almost not affected by them. But the erosion disclosed between the stations 300 m and 400 m along gate 40907-1 does extend almost 100 m into the panel 906 and almost close to the opposite gate into the panel 908. But it does not connect to the erosion disclosed along gate 40909-5. An influence of this erosion on the velocity can first be observed east of about station 20 m in gate 40909-5 but not to the amount as it can be observed for the erosion crossing the gate 40907-1 between the stations 300 m and 400 m. This was also verified by closer inspection of the observed dispersion curves through the area close to gate 40909-5 as explained above in the description of the picking procedure. The conclusion of this inspection was that the gate 40909-5 was developed within the northern border of this erosion at least in its western part. It will extend further into the panel 908 towards North-East where the ray coverage becomes coarser. It is already known that around the corner from gate 40909-5 to gate 40990-3 the coal seam is completely eroded.

6. Relation between coal seam thickness and group velocity

For the correlation of the group velocity with disclosed thickness values the erosion along the gate 40907-1 between the stations 300 m to 500 m are used as it strikes almost perpendicular into both panels. Further the thickness values in this section of the gate cover a range between less than 50 cm up to around 4 m.

Fig. 9 shows the individual correlations (symbol “x”) between the group velocity and the known thickness values which are almost arranged along a slightly curved line. From this it can be concluded that a unique correlation function must exist between these quantities. But by comparing it to the theoretical relation for the constant frequency of 200 Hz as it was derived above a great difference can be seen. Therefore it was not possible to adapt the theoretical curve to the correlation. Possible explanations for the difference might be as follows:

- (1) The known thickness values are local measures (which do contain errors) which are related to average values of the group velocity valid within the cells of the defined grid used for tomographic inversion.
- (2) It may be inherent in the tomographic inversion process as between the iteration steps smoothing was carefully applied.

Furthermore it would not be easy to use the theoretical function [7] as basis for a correlation function as it depends besides from ω and h also from the phase velocity c which is not a constant. It will depend according to [5] from the thickness h as well. Therefore to find the reason for this difference is still a matter of research.

Finally a polynomial approximation was used. Polynomials from second to fourth order were evaluated and finally a polynomial of third order was used. It is displayed in Fig. 9 as grey solid line together with the borders of the confidence interval (dashed lines above and below the solid line). It shows a possible error of about ± 10 m to ± 15 m. Towards the limit to higher velocities (thickness less than 100 cm) this error may become bigger as it approaches the value for the shear velocity in the rock. And for velocities less than about 1100 m/s (thickness greater than 300 cm) care must be taken because of the ambiguity at low velocities (see above).

Hence also the polynomial approximation may only be applied to investigate some specific thickness range. If the knowledge about a greater thickness range or even about the complete thickness variation is required the whole procedure has to be repeated for a range of constant frequency values. The final thickness map has then to be combined from the individual results.

7. The resulting thickness distribution

The derived polynomial approximation for the constant frequency value of 200 Hz was used to “translate” the distribution of the group velocity (Fig. 8) into a thickness map (Fig. 10). It shows clearly the results for the required objectives of the surveys.

- (1) The location of the eastern border of the erosion in the panel 908 disclosed between the stations 180 m and 300 m along gate 40909 is well determined by the contour line of the constant thickness of 300 cm. But the thickness values within this erosion do contain greater errors because of the limitation of the survey area.
- (2) Towards the east end of the panel 908 greater thickness variations have to be expected. The coal seam thickness might become less than 1 m (even down to 50 cm). This area will be difficult to mine. But the erosion disclosed along the west part of gate 40909-5 will not extend further towards North into this panel.
- (3) The erosions in the East and in the West along gate 40907-1 will not extend to a greater amount into the panel 906.
- (4) For the erosion disclosed between the stations 300 m and 400 m along gate 40907-1 the location of the border line for the coal seam thickness of 250 cm could be determined. Especially within the panel 906 the error in its location should be small as no further anomaly did disturb the transmission data.

These results were used by the coal mine to plan the mining of the panels in 3 steps:

- (1) The panel 908 was mined between the eastern border of the erosion located along the western border of the survey area and the erosion in the centre of the Survey Areas 1 and 2A. The mining was stopped when the seam thickness approached 200 cm.
- (2) The panel 906 was completely mined. In the area containing the erosion the width of the panel was reduced. The location for the further development of gate 40907-4 towards West was adjusted with respect to the location of the expected coal seam thickness of 250 cm. While developing the gate through the erosion thickness values between 240 cm to 260 cm and locally down to 230 cm were encountered.

- (3) An attempt was made to mine a smaller part of the coal seam in the East of the panel 908 starting gate 40907-2. For this purpose gate 40907-2 was further developed towards South by about 40 m. The mining was stopped after about 75 m because of greater thickness variations ranging between 90 cm and 240 cm.

8. Summary and conclusions

The distribution of the coal seam thickness within a panel can be investigated by means of ISS transmission surveys. In multi-layer coal seams (coal seams which do contain dirt bands) a general inversion process has to be applied for this purpose because of the greater number of quantities which have to be determined. But for a coal seam consisting of almost pure coal the inversion process can be replaced by a correlation process to receive information about the distribution of the coal seam thickness.

- (1) ISS tomography has to be applied to the group travel times for a constant frequency value which has to be selected according to the objectives of the survey. The result will be the distribution of the group velocity which will already show the location of present anomalies (erosions).
- (2) The tomographic result can be verified by inspecting the observed dispersion of the group velocity between the individual source and receiver stations.
- (3) By the correlation of known thickness values with the group velocity distribution along the gates (or part of the gates) a relation between these quantities has to be derived. This relation has to be expressed in terms of some approximation function. In this case study a polynomial approximation of third order was used.
- (4) The distribution of the coal seam thickness can be derived by applying this relation to the distribution of the group velocity.

For a constant frequency value the relation between coal seam thickness and group velocity is generally only valid for a limited thickness range. If a greater thickness range or even the complete variation of the coal seam thickness has to be investigated this procedure has to be repeated for

different frequency values. The final thickness distribution can be found by combining the results for the different frequency values.

The result can be accurate. But it can also show only a general trend about how the seam thickness may vary. It depends on if the thickness variations are located completely within the survey area or if the access from the gates is limited. Possible reasons for such limits may be missing gates, too small survey areas or additional and still unknown anomalies and disturbances.

A great difference exists between the derived correlation and the theoretical relation between coal seam thickness and group velocity. This is still a matter of current research to find an explanation for this observation.

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Figure captions

Fig. 1 Multi-layer coal seam containing several dirt bands (rock layers which again have partly some coal content).

Fig. 2 Site map of the ISS surveys showing the survey areas shaded in grey. The geological sections along the gates 40907 and 40909 show severe variations of the coal seam thickness caused by erosion. The remaining thickness of the coal seam is locally shown within circles.

Fig. 3 Dispersion curves of the group velocity for different coal seam thicknesses (theory).

Fig. 4 Dependency between the group velocity and the coal seam thickness for different constant frequency values (theory).

Fig. 5 Data from all shots along the Survey Areas 2A and 2B recorded at the receiver station G20 (X- and Y-component). The time shift in the seismic traces recorded from the shots S25 and S26 is caused by the gap between the two areas. The source stations S15 and S16 are located close to the end of gate 40907-4, which was developed into the Survey Area 2A.

Fig. 6 Results of the multiple filter analysis applied to the data from the shots at S7, S21 and S25 recorded at the receiver station G20. The results are displayed in the time domain (upper row), slowness domain (middle row) and velocity domain (lower row). The values written within the individual images are the picked values.

Fig. 7 Ray coverage map combined with the realized survey geometry (location of all source and receiver stations). It shows all ray paths for which the group traveltimes could be determined.

Fig. 8 Distribution of the group velocity for the constant frequency value of 200 Hz within the survey areas. It is obtained by the application of ISS-tomography to the recorded group travel times. It already shows the location and the extension of present erosions.

Fig. 9 Relation between the coal seam thickness and the group velocity valid for the selected frequency value of 200 Hz. A great difference between the polynomial approximation and the theoretical relation can be observed. The reason for this difference is still a matter of research.

Fig. 10 Distribution of the coal seam thickness within the survey areas. It is achieved by applying the polynomial approximation (Fig. 9) between coal seam thickness and group velocity to the result of ISS tomography application (Fig. 8).

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Fig. 1 Multi-layer coal seam containing several dirt bands (rock layers which again have partly some coal content).
171x341mm (300 x 300 DPI)

Fig. 2 Site map of the ISS surveys showing the survey areas shaded in grey. The geological sections along the gates 40907 and 40909 show severe variations of the coal seam thickness caused by erosion. The remaining thickness of the coal seam is locally shown within circles.
87x42mm (300 x 300 DPI)

Fig. 3 Dispersion curves of the group velocity for different coal seam thicknesses (theory).
85x85mm (300 x 300 DPI)

Fig. 4 Dependency between the group velocity and the coal seam thickness for different constant frequency values (theory).
85x85mm (300 x 300 DPI)

Fig. 5 Data from all shots along the Survey Areas 2A and 2B recorded at the receiver station G20 (X- and Y-component). The time shift in the seismic traces recorded from the shots S25 and S26 is caused by the gap between the two areas. The source stations S15 and S16 are located close to the end of gate 40907-4, which was developed into the Survey Area 2A.
70x57mm (300 x 300 DPI)

Fig. 6 Results of the multiple filter analysis applied to the data from the shots at S7, S21 and S25 recorded at the receiver station G20. The results are displayed in the time domain (upper row), slowness domain (middle row) and velocity domain (lower row). The values written within the individual images are the picked values.

194x208mm (300 x 300 DPI)

Fig. 7 Ray coverage map combined with the realized survey geometry (location of all source and receiver stations). It shows all ray paths for which the group traveltimes could be determined.
87x42mm (300 x 300 DPI)

Fig. 8 Distribution of the group velocity for the constant frequency value of 200 Hz within the survey areas. It is obtained by the application of ISS-tomography to the recorded group travel times. It already shows the location and the extension of present erosions.
87x42mm (300 x 300 DPI)

Fig. 9 Relation between the coal seam thickness and the group velocity valid for the selected frequency value of 200 Hz. A great difference between the polynomial approximation and the theoretical relation can be observed. The reason for this difference is still a matter of research.

60x42mm (300 x 300 DPI)

Fig. 10 Distribution of the coal seam thickness within the survey areas. It is achieved by applying the polynomial approximation (Fig. 9) between coal seam thickness and group velocity to the result of ISS tomography application (Fig. 8).
87x42mm (300 x 300 DPI)