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DETERMINATION OF SEISMIC WAVE ATTENUATION BASED ON ACOUSTIC FULL WAVEFORMS

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Abstract: The loss of elastic energy to the medium can be quantified by the quality factor Q. Acoustic full waveforms log from Winna Góra1 borehole were used to estimate P-wave quality factor. Data used in this paper were analyzed with usage of GeoWin software. Interpretation of acoustic full waveforms was performed for the one pair of waveforms. The most important part in the interpretation of data is manual picking of P wave arrival, calculation of semblance function, and picking anomalies of P wave on amplitude spectrum. Using data from interpretation of acoustic full waveforms, we calculated quality factor. Based on provided analysis it is concluded that the highest attenuation (so the lowest Q) is observed in Rotliegend strata.

Keywords: Attenuation, acoustic full waveforms, quality factor Q.

SEISMIC WAVE ATTENUATION

Attenuation of elastic waves is the phenomena of that manifests itself by the decrease of amplitudes along with time and distance, where the wave is recorded in reference to source point. Attenuation is inelastic process, where we observe constant loss of seismic energy as a result of inelastic deformations. One of the reason why attenuation occurs is redistribution of energy connected with heterogeneity of rocks. Fractures, lithological boundaries, faults and other heterogeneities cause generation of new waves at the expense of the energy of the incident wave. Another reason for at-

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tenuation of elastic waves are losses of energy, caused by high-temperature internal friction. Interaction between grains and fluids penetrating pore space of rocks, result in losses of energy at the expense of created heat (Barton, 2007).

In case of high frequencies (> 10 MHz), when the wavelength is similar to the size of grains and pores in rocks, attenuation caused by dispersion of wave on grains is dominant.

According to Johston , attenuation connected with absorption of seismic energy in rocks is the result of:

- Matrix anelasticity,
- Frictional dissipation to relative motions across crack surfaces and grain boundaries,
- Relative movements of matrix frame in vicinity of rocks saturated with fluids,

Unsteady flows („squirt" type) from micro-fractures to pore space and gas particles movements in pore space and in micro-fractures.

In general, decay of signal amplitude with distance from the source is connected with geometric spreading of wave and losses of seismic energy as a result of absorption and scattering. Geometrical spreading is phenomena of the decay of amplitude on a wavefront of seismic wave as it moves away from the source by the loss of density of the seismic energy. Absorption is connected with local loss of seismic energy as a result of conversion of energy in inelastic medium.

During the propagation of elastic wave through the medium, some of its mechanical energy is converted into heat (through friction and viscosity) on the grain boundaries and microcracks.

When seismic wave travels through rock subjected to compression and tension, fluids inside this rock are mixing with each other. Movement of the medium causes decay of amplitude. All of these factor might impact the size of the amplitude on acoustic full waveforms.

In case of seismic measurements in highly fractured zones it seems, that the greatest influence on the attenuation of seismic wave is related to absorption resulted from internal friction on the surfaces of microcracks etc. This is the view presented by Barton in reference to deformation state of medium that allows for displacement of contact area (Barton, 2007). In such conditions we observe significant impact of friction on stress level

As a fundamental measure of attenuation is assumed (Tonn, 1989):

Attenuation coefficient α

$$\alpha = \frac{1}{\Delta l}\left[\ln\left(\frac{A_1}{A_2}\right) - \ln\left(\frac{G(z_1)}{G(z_2)}\right)\right] \tag{1}$$

where: A1, A2 – amplitudes of selected phase of the wave,

Δl – tool length,

$G(z_1)$, $G(z_2)$ – geometrical spreading factor of the wave towards closest and furthest receivers.

a. Quality factor Q

$$Q = \frac{-\pi(Tpj - Tpi)f}{\ln\left(\frac{W_2}{W_1}\right)} \tag{2}$$

where: f – wave frequency,

Tpj – time of the first arrival of P wave on acoustic full waveforms recorded on more distant receiver,

Tpi – time of the first arrival of P wave on acoustic full waveforms recorded on closer receiver,

W1, W2 – amplitude spectrum of the wave, calculated for signal recorded on both receivers.

Quality factor Q is a function of wave frequency, but it is safe to assume, that in dry rocks does not depend on that parameter. It is inversely proportional to the porosity of the rock (Wawrzyniak, 2007).

Quality factor is independent of frequency, but attenuation coefficient α which is a measure of the absorption of energy, shows dependence on frequency ω:

$$\alpha = \left(\frac{\omega}{2\pi}\right)\frac{1}{Q} \tag{3}$$

High values of the quality factor mean low attenuation. Moreover higher frequencies are attenuated stronger then lower frequencies.

Based on laboratory measurements of seismic wave attenuation, we can claim that (Barton, 2007):

- Different rocks are characterized by different values of the quality factor. The highest values of Q factor are characteristic for limestone and sandstone while low values respond to shale and the lowest for gas saturated sandstones.
- The highest values of quality factor are obtained for dry rocks, lower for in the fully saturated rocks and the lowest values in partially saturated rocks.
- The Quality factor Q can be used to distinguish the content of the fluids contained in the pore space of the rock.

ACOUSTIC FULL WAVEFORMS PROFILING

Acoustic full waveforms logging based on a measurement of interval time in borehole as well as acoustic logging with full wave image are methods of measurements in open-case hole. These methods are based on the velocity of the wave travelling through geological medium.

Instrument used for the measurements is equipped with transmitters (emitting acoustic wave with frequency in range from 10 to 40 kHz). Impulse is short, and last only tens of microseconds (Paillet, 1992).

In case of acoustic full waveforms logging, we record time of the first arrival of compressional wave. Modern acoustic full waveforms logging are conducted with usage of tools, equipped with at least one transmitter (N) and two receivers: closer (O1) and further (O2) (Fig.1)

Recorded times T1 and T2 respectively for receiver closer and further, allows for calculation of travel time from the equation (4)

$$DT = \frac{T_2 - T_1}{\Delta l} \tag{4}$$

where: Δl – distance between receivers,
T1, T2 – Time.

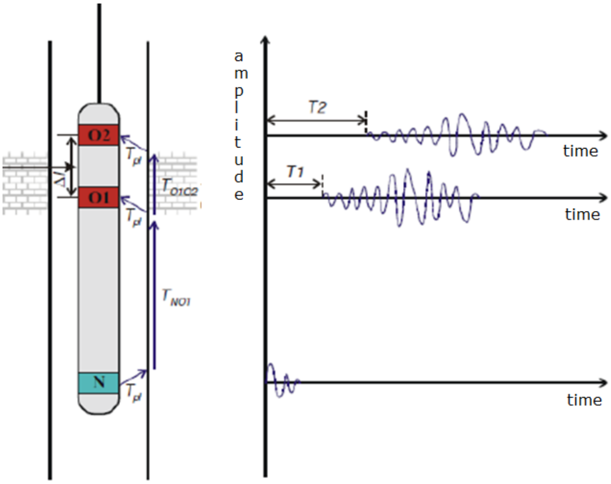

Fig. 1. Tool schema (Wawrzyniak, 2007)

Borehole where measurement is taken from must be filled with drilling mud or water. In case of empty boreholes (filled only with air), acoustic signal is completely attenuated. Strong attenuation is also observed when drilling mud is filled with gas.

Acoustic log image is the result of acoustic logging, which is a base for calculation of elastic parameters, that characterize geological medium.

Borehole acts as waveguide, being an oscillator for frequencies that depends on diameter of borehole, the angle of incidence, length and velocity of wave in drilling mud. Radiation of wave in borehole is however essentially different than the radiation of seismic wave (Wawrzyniak, 2007).

Below authors show description of waves that might be visible on acoustic full waveforms logs (Fig. 2).

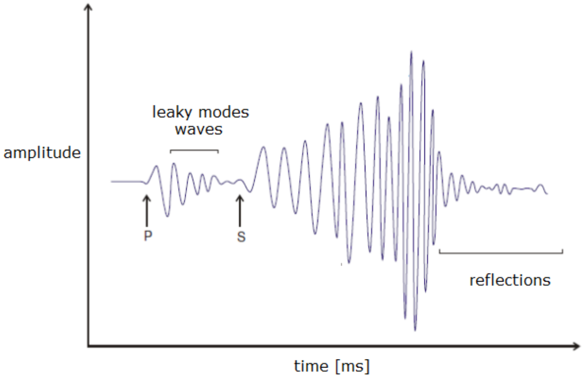

Fig. 2. Acoustic image log (Wawrzyniak, 2007)

STUDIED AREA

Data used in this article come from borehole measurements Winna Góra 1 (WG1) well, which is located nearby Poznań city in Wielkopolskie district.

Fig. 3. Localization of Winna Góra WG1 well

Tab. 1. Stratigraphy of Winna Góra 1 (WG1) well

Winna Góra 1 (WG1)		
Depth, m		Stratigraphy
Top	Bottom	
0	29	Quaternary
29	60	Pliocene
60	116	Miocene + Oligocene
116	368	J3
368	613	J2
613	978	J1
978	1966	T3
1966	2237.5	T2
2237.5	2905	T1
2905	2994.5	PZ4
2994.5	3058.5	PZ3
3058.5	3307	PZ2
3307	3520	PZ1
3520	3652	Rotliegend

INTERPRETATION OF ACOUSTIC FULL WAVEFORMS LOG

Data used in this paper were analyzed with usage of GeoWin system. This software was developed thanks to cooperation between department of Geophysics at AGH and Geofizyka Krakow company. This software contains full set of procedures allowing to perform all necessary steps with regards to qualitative and quantitative processing of well log data.

Interpretation of acoustic full waveforms (Fig. 4) was performed for the pair of wave images WF1-WF4, that corresponds to the greatest distance from receivers.

Conducted interpretation was based on:

- Picking times of the first arrivals of P and S wave, on both chosen receivers, e.g. WF1-WF4,
- Calculating the semblance function,
- Picking anomalies of P and S waves on the amplitude spectrum of the signal.

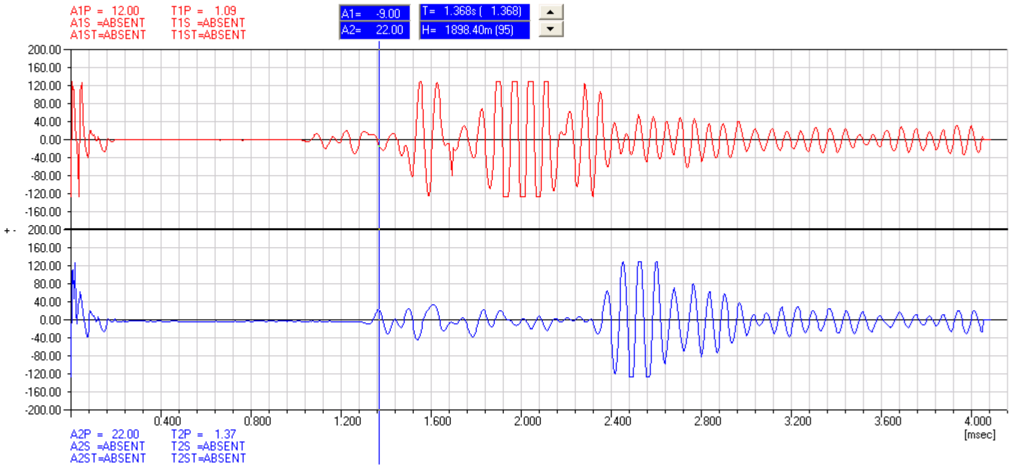

Fig. 4. Acoustic full waveforms data, set WF1 – WF4, record nr. 95

While picking time of the P wave first arrival, author abide the rule of the correctness of record. This means that P wave should arise earlier on the closer receiver and its amplitude should be higher on it.

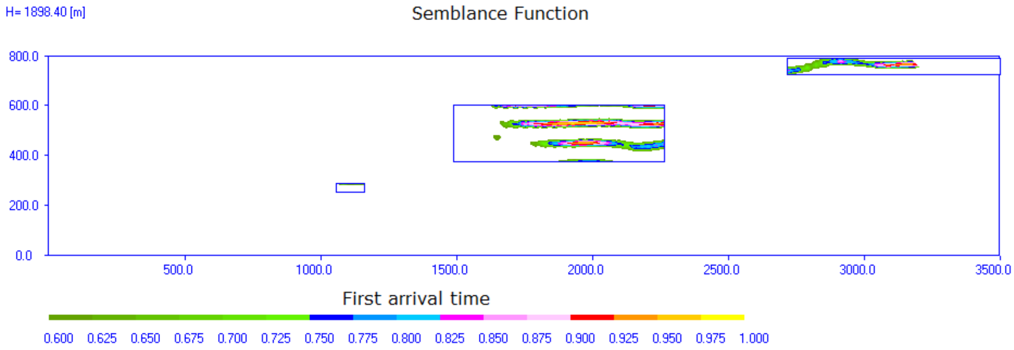

Fig. 5. Semblance function, Pair WF1 – WF4, record nr. 95

Semblance function (Fig. 5) is the function of similarity, and it is calculated in the time domain. This function is used as a measure of coherence of multichannel acoustic records. Value of that function is in the range [0, 1]. When semblance function has value equal to 1, it means that all acoustic full waveforms data used for the calculation of that function are the same, both in shape and amplitude. Function maxima are interpreted as time of arrivals T1 and interval times DT, respectively for P, S and Stonley wave. Accuracy of the method that is based on calculation of semblance function depends directly to the number of receivers, and it is high for multichannel registration, so for one pair on receivers accuracy is rather low (Wawrzyniak, 2007).

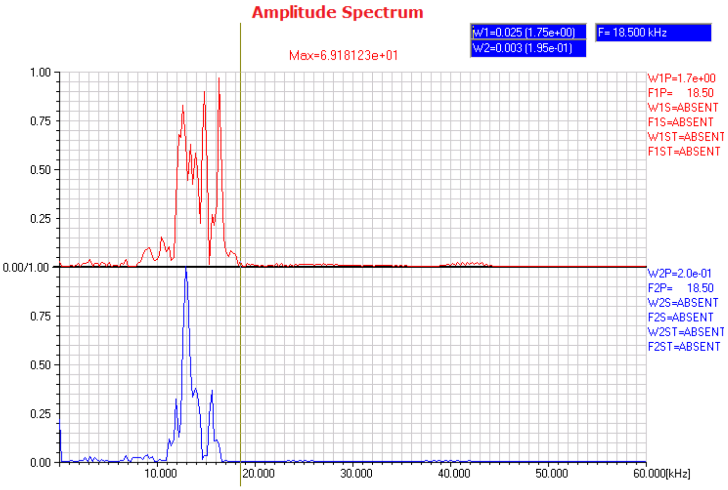

Fig. 6. Amplitude spectrum, Pair WF1 – WF4, record nr. 95

Spectrum of amplitude (Fig. 6) in GeoWin software is normalized to the range from 0 to 1, so the first arrival of P wave is shown as a small pick, with frequency not higher than 20kHZ.

ESTIMATION OF Q FACTOR BASED ON AOF

Next step after completing interpretation procedures is calculating the attenuation coefficient of elastic waves.

Analyzed records of acoustic full waveforms, has shown many hard to explain examples of the oscillations of amplitudes in time domain, and as hard examples on amplitude spectrums. There might be at least few reasons for that, e.g. some parts of the record are effected by errors or we deal for some time with inadequate orientation of the instrument in the borehole.

Nevertheless it was possible to choose sufficient amount of the record to be able to calculate quality factor Q for lithostratigraphic formations recognized in boreholes in the area of study.

Quality factor Q was used as measure of attenuation. It was calculated with usage of equation 2.

Results of calculations are shown in Tab 2. The closest and furthest receivers correspond to acoustic full waveforms, respectively WF1 – WF4. Table 2 contains results of the calculation of the Q for each stratigraphic formation. Authors focused only on identification of first arrival of P wave, because arrival identification for S wave was very unclear and should be a subject for further analysis.

Tab. 2. Attenuation coefficient Qp for lithological formations from Winna Góra 1

Formation	Top	Bottom	Qp			
			Min	Max	Mean	St. dev
J3	116,00	368,00	10,17	26,84	16,34	5,58
J2	368,00	613,00	3,97	48,97	18,11	12,59
J1	613,00	978,00	3,45	96,19	28,28	26,04
T3	978,00	1966,00	2,69	121,91	21,20	20,46
T2	1966,00	2237,50	1,96	76,89	11,75	14,36
T1	2237,50	2905,00	1,63	108,75	13,53	16,63
PZ4	2905,00	2994,50	6,70	18,83	12,24	5,01
PZ1	3307,00	3520,00	3,20	28,95	11,62	7,67
Rotliegend	3520,00	3652,00	8,75	19,90	14,88	4,62

RESULTS AND CONCLUSIONS

Conducted analysis, proved that attenuation, measured in terms of quality factor Q is highly dependent on lithology.

Quality factor was calculated for nine stratigraphic intervals from 116 to 3520 m. The lowest value for Q, so the biggest attenuation, is observed in Rotliegend strata. The smallest attenuation, so the highest value for Q, is in J1 strata.

Further analysis is required for more precise identification of P and S wave on acoustic full waveforms both in time and frequency domain.

Surface layer was not the subject of analysis in this study but is seems to be very reasonable to calculate quality factor also for this zone, since its believed that this zone is highly attenuated.

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