EÖTVÖS LORÁND GEOPHYSICAL INSTITUTE OF HUNGARY
GEOPHYSICAL TRANSACTIONS 1982
28/1 pp. 73–85

DETERMINATION OF ATTENUATION FROM REFLECTION SEISMIC DATA AND THE INFLUENCE OF LAYERING

U. PATZER*

When developing new seismic processing techniques it is of great importance to test them with synthetic traces. Very often this step is decisive. Comparison of the obtained processing results with the known model data allows one to draw conclusions on the general performance, the optimum parameters, and the effectiveness of the technique under actual conditions.

As is demonstrated with a specific technique of attenuation determination the result obtained from such synthetic computations depends essentially on the reflection coefficient series from which the synthetic trace is computed. Unsuitable model traces can lead to incorrect assertions on the achievable accuracy and consequently on the potential practical effectiveness of the technique.

1. Problem discussion

A seismic trace $x(t)$ is considered to be the convolution of a reflectivity derived spike series with a wavelet

$$x(t) = i(t)\, s(t).$$

The spike series $i(t)$ represents the acoustic impedance distribution in the subsurface. While travelling underground the spectral composition of a seismic wavelet $s(t)$ is changed mainly as a result of attenuation. If the attenuation coefficient is to be determined from this spectral change the problem arises of extracting the wavelet spectrum from the seismic trace.

There exist several techniques to eliminate the influence of the spike series to such a degree that a sufficiently accurate estimation of the wavelet spectrum can be achieved. Their effectiveness is commonly tested with synthetic data. It is a general experience that the attenuation distribution computed from synthetic seismograms depends essentially on the used layer or velocity model (Baruli et al. 1980), in some cases the influence of the spike series may be so great that no meaningful attenuation determination can be achieved (Millahn and Jurczyk 1977, Engelhard 1978).

It is possible that the used technique does not enable a clear separation of the parts $s(t)$ and $i(t)$. Furthermore, the accuracy largely depends on the type of model used for the theoretical analyses. These two effects will be illustrated by a typical example in *Fig. 1*. First of all it can be established that the cepstrum analysis generally yields a more exact estimation of the actual wavelet spectra than the autocorrelation function technique of Rapoport (1969) where great deviations from the true spectra occur if an actual reflection coefficient series is applied.

* VEB Geophysik Leipzig, GDR.
Paper presented at the 26th Geophysical Symposium, Leipzig, 22–25. September, 1981.

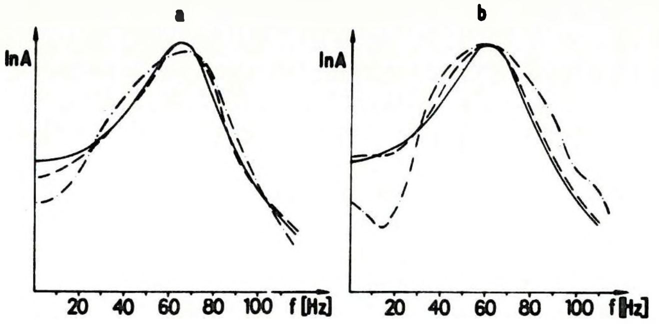

Fig. 1. Wavelet spectrum estimation from synthetic seismic traces
a — spike series of random distribution; b — actual reflection coefficient series
——— given spectrum, –––– spectrum obtained by cepstrum analysis,
–·–·– spectrum obtained from the autocorrelation function

1. ábra. Az elemi jel spektrumának becslése szintetikus szeizmogramokból
a — véletlen eloszlás impulzussorozata; *b* — tényleges reflexiós koefficiens sorozat
——— tényleges spektrum, –––– cepstrumanalízissel kapott spektrum, –·–· autokorrelációs függvénnyel számított spektrum

Фиг. 1. Оценка спектра сигнала для синтетической сейсмической трассы
а — последовательности импульсов по случайному распределению; b — реальная последовательность коэффициентов отражения
заданный спектр, –––– спектр по кепстральному анализу, –·–·– спектр по функции автокорреляции

2. Models and test computations

Test computations were carried out on models derived from the velocity distribution of a well located in the North German–Polish Basin. No density values were available.

In model A of Fig. 5 the constant velocity layers were derived from the lithologic coloumn taking into account the acoustic log as well as petrophysical data. The mean layer thickness amounts to about 30 m. In the depth section corresponding to a traveltime range of 1.0 to 2.8 s acoustic log data were available. Models B and C, sampled at 10 m and 2 m rates, respectively, resulted from these data. All models are presented on the left part of Fig. 5 (for the traveltime interval 1.4 to 2.3 s).

In Fig. 1 the connection between the quality of spectrum estimation and the type of distribution of the used spike sequences is shown. Further special investigations were carried out based on model C. To have a better approximation of the actual conditions the data sampled with a 2 m rate were transformed into the time domain. Following Baranov and Kunetz (1960) the medium, assumed as ideally elastic, was subdivided into equal traveltime (in this case 1 ms), constant velocity layers. Thus, separate analyses of the influence of transmission and that of the multiples on the reflection coefficient series can be simultaneously made.

The randomness of the reflection coefficient series computed in this manner can be checked using the autocorrelation function. The autocorrelation function of a true random series only deviates significantly from zero for the time shift $\tau=0$. If $\tau \neq 0$ the values must be within a threshold level of significance, this threshold depends on both the false rejection probability and width of the analysed interval. The false rejection probability was selected as 5% for all investigated cases. For example, using an analysis window of 0.2 s some 15% of the peak value of the autocorrelation function corresponds to the threshold of significance.

Figure 2 shows the sampled, normalized autocorrelation function for different positions of the analysed traveltime window (the above mentioned threshold is also given). At narrow windows (0.2 and 0.4 s) significant differences in the character of the autocorrelation function can be seen for adjoining traveltime windows. In most cases there are several extrema exceeding the threshold of significance. This clearly indicates that the reflection coefficient series are generally *not* randomly distributed.

This general statement is also valid when the analysed window is enlarged up to an interval corresponding to the so-called effective time window (0.8 s) used for the attenuation determination. The intensity of the secondary extrema at time shifts $\tau \neq 0$ is somewhat lower for the summarized coefficient series (d) compared with the other ones (a, b, c). But in each case there also occur individual peaks exceeding or coming close to the threshold value.

Further analyses using actual reflection coefficient series show that in general they obey a normal distribution. This is demonstrated in more detail in Patzer et al. (1981). The evaluation given above is in good agreement with the results obtained by Agard and Grau (1961).

Returning to the results presented in Fig. 1, we have seen how much the quality of spectrum estimation from the autocorrelation function depended on the type of distribution. For the cepstrum analysis the most suitable type of distribution is obviously a random reflection coefficient series. However, the deviations of the actual reflection coefficient series from this type of distribution have not such a strong effect on wavelet spectrum estimation as in case of the autocorrelation function method. We have found that when using cepstrum analysis with optimally selected program parameters, it yields an approximately four times higher accuracy in attenuation determination than that achieved with the autocorrelation function technique.

3. The influence of intrabed multiples

The term "attenuation" generally describes the frequency dependent energy losses of a seismic wave due to its propagation through the medium. This energy loss is esentially caused both by the nonreversible change of mechanical energy into heat and by wave scattering at interfaces and other inhomogeneities. If a seismic signal travels through a layered medium an additional attenuation mechanism acts. It results from the combination of transmission losses at inter-

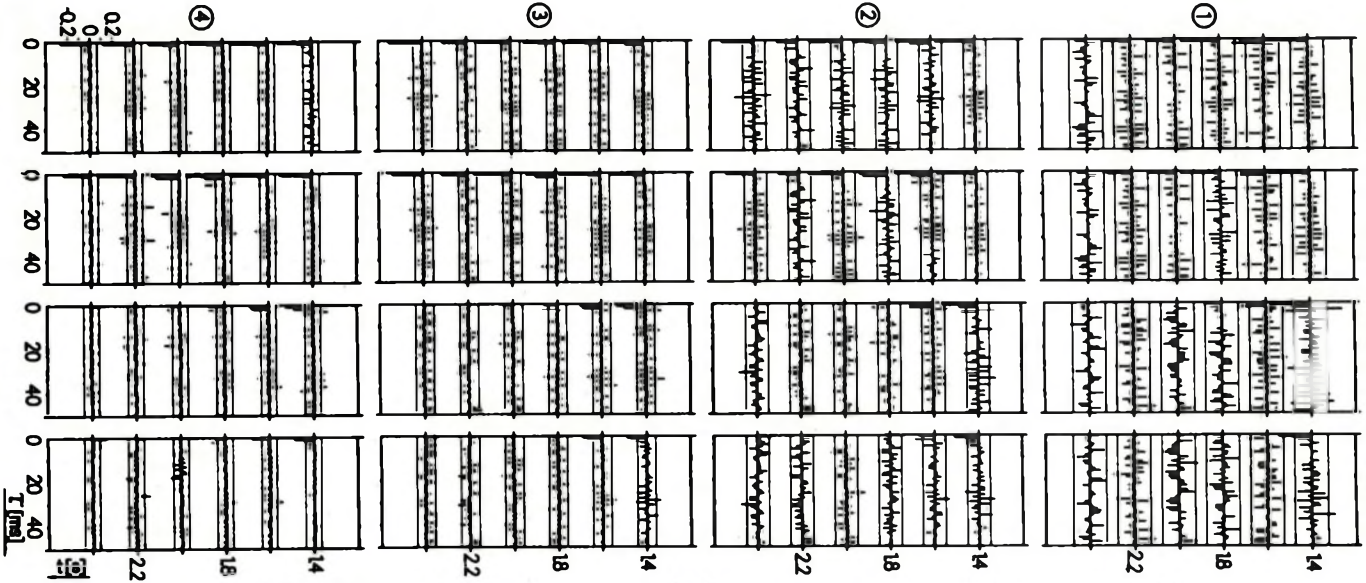

Fig. 2. Sampled autocorrelation functions of reflection coefficient sequences derived from model C

a — normal reflection coefficient sequence; b — reflection coefficient sequence including transmission loss; c — reflection coefficient sequence of multiple reflections; d — summarized reflection coefficient sequence ($b+c$)

1 — time window 0.2 s, 2 — time window 0.4 s, 3 — time window 0.6 s, 4 — time window 0.8 s

2. ábra. C modellből származtatott reflexiós koefficiens sorozatok mintavételezett autokorrelációs függvényei

a — kiinduló reflexiós koefficiens sorozat; b — reflexiós koefficiens sorozat az áthaladási veszteségek figyelembevételével; c — többszörösök reflexiós koefficiens sorozata; d — összegezett reflexiós koefficiens sorozat ($b+c$)

1 — időablak 0,2 s; 2 — időablak 0,4 s; 3 — időablak 0,6 s; 4 — időablak 0,8 s

Фиг. 2. Полученные в результате квантования функции автокорреляции для последовательности коэффициентов отражения, выведенных по модели C

а – нормальная последовательность коэффициентов отражения; b – последовательность коэффициентов отражения с учетом потерей по передаче; c – последовательность коэффициентов отражения для многократных отражений; d – накопленная последовательность коэффициентов отражения ($b+c$)

1 – временное окно 0,2 с, 2 – временное окно 0,4 с, 3 – временное окно 0,6 с, 4 – временное окно 0,8 с

faces and intrabed multiples generated therefrom. In particular, when a seismic wave travels through a stack of thin layers of strongly changing acoustic impedances an essential fraction of the signal energy gets trapped and only reappears of greater traveltimes. Hence, the maximum amplitude decreases and the predominant frequency of the signal is lowered. Although the mechanism is of an entirely different kind from that caused by inelasticity and scattering, its action on the seismic pulse is very similar. This "quasiattenuation" effect was clearly described by O'Doherty and Anstey (1971). For our investigations it is of interest to what extent this apparent attenuation due to intrabed multiples acts in the used models. The investigations were carried out again on layer model C. The reflection coefficient series was computed according to Baranov and Kunetz's technique (1960).

Similarly to the method suggested by Schoenberger and Levin (1974), the model was sealed at the bottom of the hole by an additional isolated totally reflective interface of reflection coefficient $R = -1$. In the computed reflection coefficient series involving all true and multiple reflections each reflection generated at this reflective horizon represents that energy which has travelled downward and upward through the layer model.

For computational reasons the additional reflective interface was inserted at 2 s traveltime. *Figure 3* shows that at this traveltime the multiple tail of the original model is not entirely suppressed and superimposes on the reflections gener-

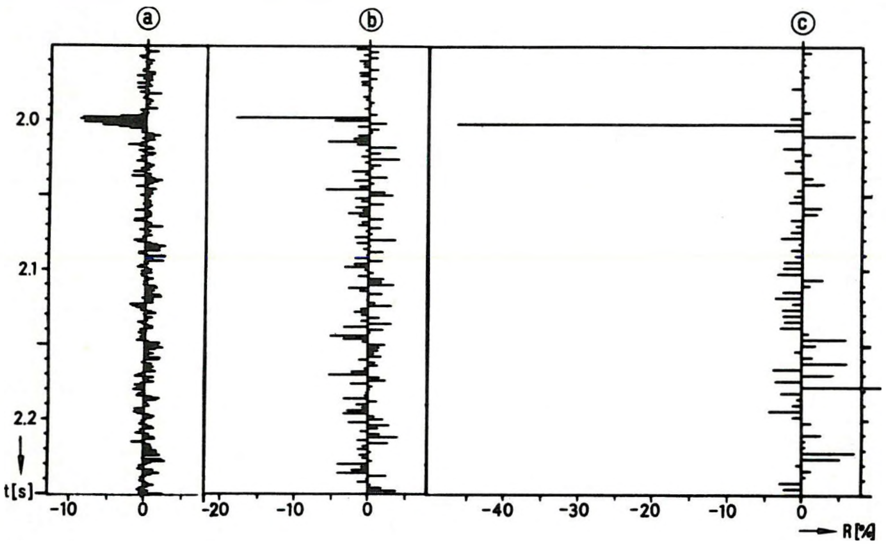

Fig. 3. Impulse response for a spike travelling twice through model C for different sampling rates
a — sampling rate 1 ms; b — sampling rate 2 ms; c — sampling rate 4 ms

3. ábra. Impulzus-válaszfüggvény, a C modellen való kétszeri áthaladás esetén, különböző mintavételezéssel
a — mintavételi köz 1 ms; b — mintavételi köz 2 ms; c — mintavételi köz 4 ms

Фиг. 3. Характеристика импульса, проходящего два раза модель слоистости C при разных шагах квантования в диапазоне времени
a — шаг квантования 1 мс; b — шаг квантования 2 мс; c — шаг квантования 4 мс

ated at the isolated reflective interface. Nevertheless, the model allows qualitative assertions about the filtering effect of the original series of layers.

As can be seen from Fig. 3, the impulse response exhibits considerable differences depending on the sampling rate used for the computation of the reflection coefficient series (see also SCHOENBERGER and LEVIN 1979).

The shift of a considerable fraction of the reflected energy towards greater traveltimes with simultaneous pulse broadening (typical for a cyclic layering according to O'DOHERTY and ANSTEY 1971) becomes clear only when applying a sampling rate of 1 ms, in spite of the great thickness of the analysed layer complex.

The amplitude spectra of the impulse responses *(Fig. 4)* show that for sampling rates greater than 2 ms the frequency dependent attenuation caused by intrabed multiples can be neglected.

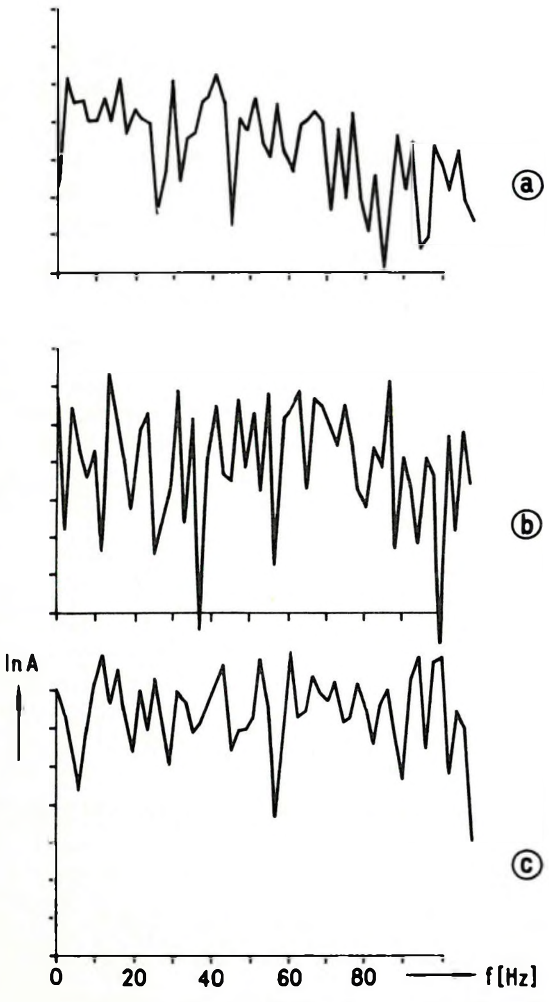

Fig. 4. Amplitude spectra of the impulse responses presented in Fig. 3
a — sampling rate 1 ms; b — sampling rate 2 ms; c — sampling rate 4 ms

4. ábra. A 3. ábrán bemutatott impulzusválaszfüggvények amplitúdóspektrumai
a — mintavételi köz 1 ms; b — mintavételi köz 2 ms; c — mintavételi köz 4 ms

Фиг. 4. Амплитудные спектра характеристик импульсов, приведенных на рис. 3
a – шаг квантования 1 мс; в – шаг квантования 2 мс; с – шаг квантования 4 мс

4. Computation of synthetic seismograms with attenuation and attenuation determination

The investigations on the influence of the selected layer model on the accuracy of attenuation determination were accomplished on synthetic traces computed by taking into account attenuation. First of all the complex frequency characteristics of the model were determined by applying Fourier transform to the spike series including all primary and multiple reflections (Gogonenkov and Zacharov 1971). A linear dependence of attenuation on frequency was assumed. Velocity dispersion was taken into account according to the well-known Futterman relation connecting attenuation and dispersion. We started out from different attenuation functions, derived the spikes series for the models A to C, and convolved the results by an actual wavelet recorded near one of the shotpoints.

The computation of attenuation was carried out by the computer program ABSOR2. The signal spectrum is determined by cepstrum analysis within moving time windows shifted in 50 ms steps along the trace. The effective length of this window and hence the resolution power of attenuation determination is approximately 0.8 s. An earlier version of this technique was presented at the 22nd Geophysical Symposium held in Prague [Danckwardt et al. 1978]. The attenuation coefficient α is assumed to depend linearly on frequency, $\alpha(f) = k \cdot f$. The factor k of dimension $m^{-1} Hz^{-1}$ is computed in the well-known manner from the slope of the spectral ratios. This value, reflecting the change of the ratios between high- as well as low-frequency signal components is denoted by k_f.

In the extended version of the program [Danckwardt and Patzer 1981] the attenuation is additionally computed from the traveltime dependent amplitude decay for the same harmonic components of the signal spectrum (attenuation value k_t). Besides the determination of the individual values k_f and k_t the program also computes the summarized attenuation coefficient $k_\Sigma = 1/2(k_f + k_t)$.

5. Analysis of the influence of layering

First, the processing results obtained for model A are considered. In *Fig. 5* (upper part) it can be seen that a very high deviation occurs from the actual attenuation value. The greatest error arises in k_t, computed from the traveltime-dependent amplitude decay.

From *Fig. 6* (left part) it is clearly seen that the character of the distribution of the results is not changed if different attenuation functions are assumed. The mean deviation from the true attenuation value remains approximately constant. This means that the accuracy of the attenuation determination is independent of the actual magnitude of attenuation.

The causes of these great errors can be attributed mostly to the insufficient suppression of the spike series. The right-hand side of Fig. 6 shows the difference curves for the computed attenuation. Subtracting the curves based on the

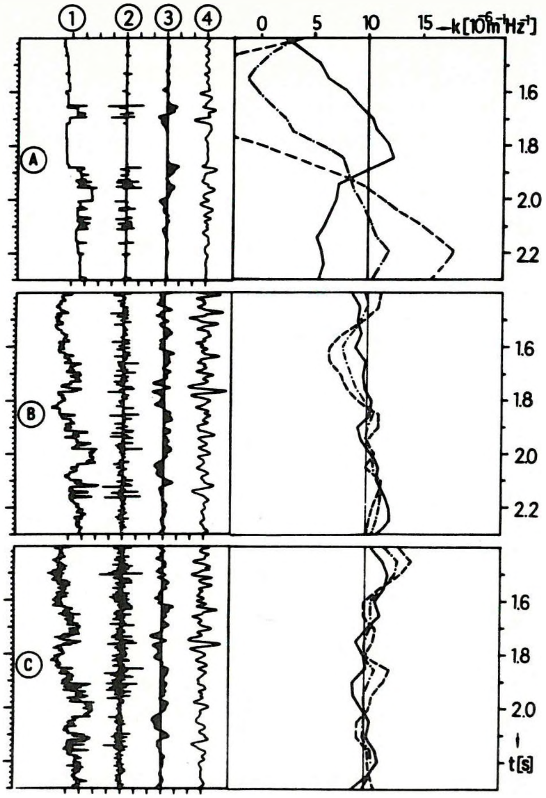

Fig. 5. Attenuation determination from synthetic traces for different velocity distributions and different models

A — based on lithology (mean layer thickness 30 m); B — resulting from acoustic log, sampling rate = 10 m; C — resulting from acoustic log, sampling rate = 2 m

1 — velocity distribution, 2 — reflection coefficient series, 3 — attenuation affected reflected impulses, 4 — synthetic trace after convolution of 3 by a wavelet (attenuation: model 1 with $k = 10$), computed values for k_f ———, k_t – – – –, k_Σ – · – · –

5. ábra. Csillapodás-meghatározás szintetikus szeizmogramokból különböző sebességeloszlásokra és különböző modellekre

A — a fúrási szelvényből (átlagos rétegvastagság 30 m); B — akusztikus szelvényből, mintavételi köz 10 m; C — akusztikus szelvényből, mintavételi köz 2 m

1 — sebességeloszlás, 2 — reflexiós koefficiens sorozat, 3 — csillapított reflektált impulzusok, 4 — szintetikus szeizmogram (3 konvolválva egy elemi hullámmal) az adott csillapítással (modell 1, $k = 10$), számított értékek: k_f ———, k_t – – – –, k_Σ – · – · –

Фиг. 5. Результаты определения поглощения по синтетическим тестовым трассам, которые получены с применением различных законов скоростей и моделей слоистости

А — по литологическому разрезу, средняя мощность пластов 30 м; В — по акустическому каротажу, шаг квантования = 10 м; С — по акустическому каротажу, шаг квантования = 2 м

1 — распределение скорости, 2 — последовательность коэффициентов отражения, 3 — импульсная трасса с учетом поглощения, 4 — синтетическая трасса после свертки импульсной трассы 3 с сейсмическим сигналом (заданное поглощение: модель 1 с к = 10), рассчитанные значения для k_f ———, k_t – – – –, k_Σ ——

attenuation functions 1 ($k = 10 \times 10^{-6}$ m^{-1} Hz^{-1}) and 2 ($k = 5 \times 10^{-6}$ m^{-1} Hz^{-1}), respectively the above mentioned difference curves result. As can be seen, a significant decrease of the deviation from the given attenuation model is achieved. But this correction for layering effects is only of a hypothetical value as it is not applicable to actual data.

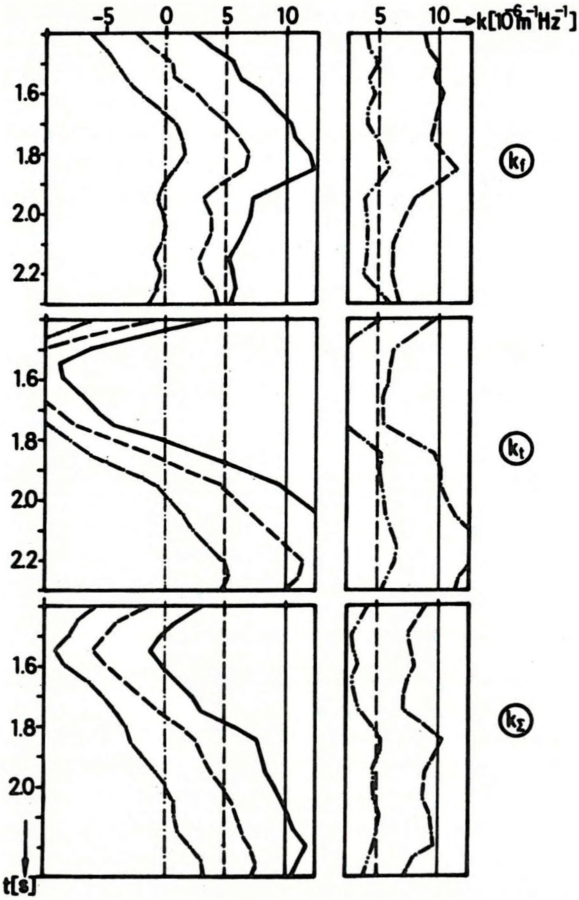

Fig. 6. Attenuation determination from synthetic traces, velocity model A
——— data for model 1 ($k = 10$), ---- data for model 2 ($k = 5$), -·-·- data for model 3 ($k = 0$), --·-- difference between the values for models 1 and 3, --··-- difference between the values for models 2 and 3

6. ábra. Csillapodás-meghatározás szintetikus szeizmogramokból, A sebességmodellre
——— adatok modell 1-hez ($k = 10$), ---- adatok modell 2-höz ($k = 5$), -·-·- adatok modell 3-hoz ($k = 0$), --·-- 1. és 3. modellre számított értékek különbsége, --··-- 2. és 3. modellre számított értékek különbsége

Фиг. 6. Результаты определения поглощения на тестовых синтетических трассах модели слоистой среды А
данные для модели 1 ($\kappa = 10$), ---- данные для модели 2 ($\kappa = 5$), -·-·- данные для модели 3 ($\kappa = 0$), --·-- разница между данными моделей 1 и 3 --··-- разница между данными моделей 2 и 3

If the test result obtained from this layer model had been available it would have been possible to conclude that the used technique does not enable a sufficient suppression of the spike series influence and is unsuitable for detecting attenuation anomalies under actual conditions.

But when using more detailed layer models which may be derived from acoustic log data (models B and C in Fig. 5) an essentially smaller deviation between computed and given attenuation values is achieved. According to Table I the mean deviation is only as small as about $1 \times 10^{-6}\ \mathrm{m}^{-1}\ \mathrm{Hz}^{-1}$ for this model. If a value of $10 \times 10^{-6}\ \mathrm{m}^{-1}\ \mathrm{Hz}^{-1}$ is taken for the average attenuation in the subsurface under normal conditions, a theoretical accuracy of about 10% is achieved in determining attenuation. Under such circumstances the application of the described technique to practical exploration problems seems more favourable than in the case of layer model A.

Table I. Accuracy of attenuation determination depending on the sampling rate of an actual velocity model

Layer model	Layer thickness		Mean deviation m_k in $10^{-6}\ \mathrm{m}^{-1}\ \mathrm{Hz}^{-1}$		
	in m	in ms	m_{k_f}	m_{k_r}	m_k
A	≈30	≈15	2.5	9.3	4.0
B	10	≈ 5	0.9	1.2	0.9
C	2	≤ 2	0.9	1.2	0.8

6. Detection of Attenuation Anomalies

To prove the general performance of program ABSOR2 in predicting layers with increased attenuation the computations were repeated for model C using a modified attenuation function (attenuation model 4). When evaluating the data presented in *Fig. 7*, it must be considered that because of the limited vertical resolving power of the technique a strong smoothing of the attenuation distribution results. The theoretically achievable representation of the anomaly (dotted line) depends on both the magnitude of the attenuation anomaly (length 0.3 s, change of attenuation by $10 \times 10^{-6}\ \mathrm{m}^{-1}\ \mathrm{Hz}^{-1}$) and on the resolving power of the computation (0.8 s).

Taking these facts into account a satisfying approximation of the computed attenuation values to the theoretically achievable curve can be established for attenuation model 4. A reliable detection of attenuation changes of such a magnitude seems to be somewhat problematic for actual conditions. Obviously, such anomalies are at the lower boundary of detectability when using program ABSOR2.

The subtraction of data for attenuation function 1 (with anomaly) from those corresponding to function 4 ("normal level" of attenuation), already demonstrated in Fig. 6, yields a decrease of deviations—but not decisive—between theoretical and computed values. Also in this case, the improvement results from the elimination of the residual layering influence. As follows from Fig. 7, this influence of the spike series for layer model C is not very high, it is in the order of the inevitable inaccuracies of the computational technique.

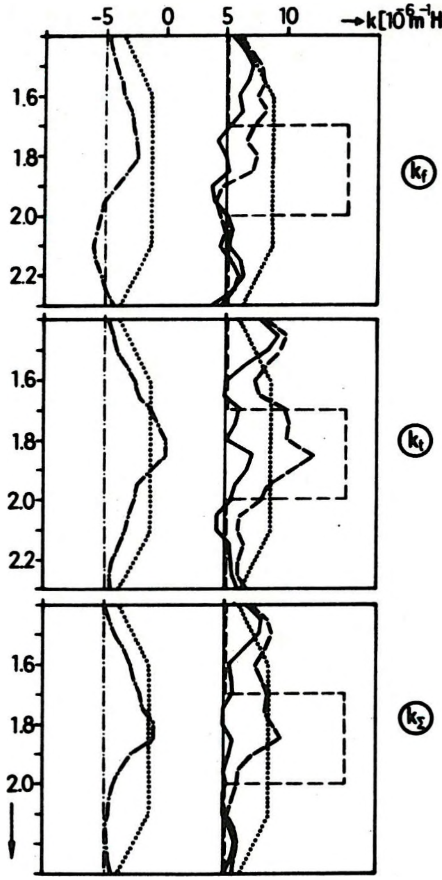

Fig. 7. Attenuation determination from synthetic traces, velocity model C
——— data for model 1 ($k=10$), ---- data for model 4 (interval 1.7 to 2.0 s, $k=20$, outside this interval $k=10$), -·-·- difference between the values for models 1 and 4, ... theoretical distribution of the results for model 4 for the given resolving power

7. ábra. Csillapodás-meghatározás szintetikus szeizmogramokból, C sebességmodell
——— adatok modell 1-hez ($k=10$), ---- adatok modell 4-hez (az 1,7—2,0 s intervallumon belül $k=20$, ezen kívül $k=10$), -·-·- 1. és 4. modellre számított értékek különbsége, ... az eredmények elméleti eloszlása a 4. modellre, az adott felbontóképesség mellett

Фиг. 7. Результаты определения поглощения на тестовых синтетических трассах модели слоистой среды С
данные для модели 1 ($\kappa = 10$), --- данные для модели 4 (в интервале от 1,7 до 2,0 с, $\kappa = 20$, вне этого окна: $\kappa = 10$), -·-·- разница между данными моделей 1 и 4, ···· теоретическое распределение данных для модели 4, получаемое с учетом разрешающей способности

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ULRICH PATZER

A RÉTEGZŐDÉS HATÁSA A CSILLAPODÁS MEGHATÁROZÁSÁNAK PONTOSSÁGÁRA

Szintetikus csatornákon végzett elméleti számításokból ismeretes, hogy a rétegzett közeg modellje jelentős hatást gyakorol a csillapodás számításának pontosságára. Az alkalmazott eljárások valószínűleg nem adnak módot ezen hatás kiküszöbölésére. Ezenkívül az elérhető pontosság jelentős mértékben függ az elméleti analíziseknél alkalmazott, rétegzett modell fajtájától.

Vizsgálatokat végeztünk olyan modelleken, amelyek különböző részletességgel tükrözték a fúrólyukakban meghatározott sebességeloszlásokat. A szelvény durva tagolása alapján kapott sebességmodell felhasználásakor igen nagy mérési hiba figyelhető meg, ez azzal kapcsolatos, hogy a modell nem elég részletesen tükrözi a valóságos viszonyokat. A rétegzett közegen — akusztikus karotázs alapján, csökkentett mintavételi közzel — végrehajtott elméleti számítások alátámasztják ezt a következtetést, a számított abszorpciós értékek sokkal kisebb mértékben térnek el a megadottaktól.

У. ПАТЦЕР

ВЛИЯНИЕ СЛОИСТОСТИ НА ТОЧНОСТЬ ОПРЕДЕЛЕНИЯ ЗАТУХАНИЯ

По теоретическим расчетам с синтетическими трассами известно, что модель слоистой среды оказывает существенное влияние на точность расчета затухания. Применяемые способы очевидно не позволяют исключить этот эффект. Кроме того, достигаемая точность в значительной мере зависит от вида слоистой модели, применяемой при теоретических анализах.

Исследования проводились на моделях, которые отражали распределения скоростей, определенные в скважине, с разной степенью детальности. При использовании модели скорости, полученной по грубому расчленению разреза, наблюдается очень большая ошибка измерения, которая получается из-за того, что модель недостаточно детально отражает реальные условия. Этот вывод потверждается теоретическими расчетами на модели слоистой среды с уменьшенным шагом квантования по акустическому каротажу, причем расчетные значения поглощения в значительно меньшей мере отличаются от заданных.

Készült a Prospektagent Gmk gondozásában,
Szedte a Nyomdaipari Fényszedő Üzem

Statisztikai Kiadó Vállalat
Felelős vezető: Kecskés József igazgató
Nyomdaüzem – 82–5265–09
Budapest, 1982
Terjedelem: 7,7 A/5 ív