GEOPHYSICAL TRANSACTIONS 1985
Vol. 31. No. 4. pp. 391–403

FREQUENCY CONTENT OF SEISMIC WAVES AS A FUNCTION OF CHARGE

Hans RISCHE*

In test-measurements aimed at determining the influence of charge quantity on the frequency content of seismic waves the known relation $A = kQ^p$ was checked and improved to $p = a - b \cdot$ frequency. This relation is an adequate approximation for describing the depedence of the spectral amplitude behaviour on the quantity of charge.

Keywords: reflection method, shot-generation, charge quantity, frequency content, field tests

1. Introduction

It is well known that, in onshore seismic work, shot generation creates the best conditions for extending the effective frequency band of the seismic waves in the direction of the higher frequencies (high-frequency seismics). This extension is necessary in order to meet one of the most important requirements of geological exploration – better horizontal and vertical resolution. It can already give quite remarkable results in the presence of excellent excitation, propagation and reception conditions, and in cases where suitable generation and reception techniques are used [FARR 1976].

The essential parameters for shooting are the quantity and the depth of the charge (bearing in mind the properties of the rock close to the surface). While the depth of the charge in high-frequency work is necessarily below the low-velocity layer or in the solid rock, the only requirement for the quantity of charge is that it should be as small as possible.

Similar requirements on the quantity of the charge result when seismic waves are generated at very shallow depths [RISCHE 1985]. This technique is used particularly in cases where there is a cost limit on field work. The shooting then takes place for the most part only a few metres below ground level in the low-velocity layer. Here again the quantity of charge must be small for the technique to be successful, as has been shown by examples in exploration practice [GAERTNER et al. 1985].

* Karl-Marx-Universität, Sektion Physik, Talstr. 35, 7010 Leipzig, GDR
Manuscript received: 28 March, 1985

2. Known relations

From theoretical considerations it follows for longitudinal body waves that

$$\text{amplitude, } A = k_1 Q^{1/3}$$
$$\text{period, } T = k_2 Q^{1/3}$$
$$\text{dominant frequency, } f_0 = k_3 Q^{-1/3}$$

(Q = quantity of charge, k_1 = material-dependent factors).
Considering plane compressional waves, on the other hand, it follows that

$$A = kQ^{1/2}$$

In most cases, these relations provide the only basis for influencing the frequency content of seismic waves using the quantity of charge [ZIOLKOWSKI and LERWILL 1979].

When a charge/amplitude relation is empirically determined the result is

$$A = kQ^p$$

where p can have quite different values. According to MEISSNER and STEGENA [1979], for example, the range for p may be

$$0.5 < p < 1.3.$$

Too little is known as yet about the way in which p depends on the specific shot conditions, and no formulation exists so far.

The data published for p so far indicate that this exponent should depend also on the quantity of the charge, Q. Thus LEVYANT [1964] reported experimental results and determined

$$p = 0.85 \text{ for } 0.4 < Q < 2.5 \text{ kg},$$
$$p = 0.55 \text{ for } 2.5 < Q < 10 \text{ kg}.$$

Fig. 1 shows the values found.

Similar findings have been reported for the apparent frequency, f_0, but less experimentation has been done to verify these. What is mostly found is

$$f_0 = KQ^{-1/3} \ldots\ldots\ldots\ldots KQ^{-1/2}$$

where the exponent $-1/3$ is derived from theoretical considerations whereas $-1/2$ is derived from experimental data. Since a considerable range of scattering exists for the charge/amplitude relation whose dependence on the shot conditions is largely unknown, a situation which is at least of similar uncertainty must be assumed for a charge/frequency relation. However, too few experimental results have been published so far for a quantitative determination of the range of this exponent.

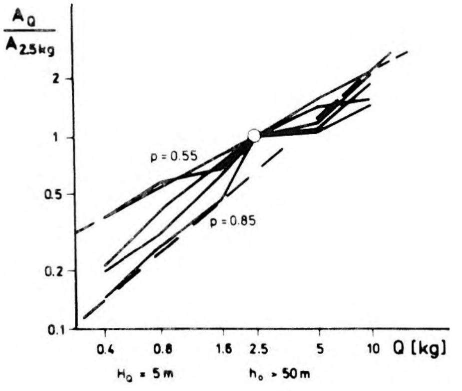

Fig. 1. Total amplitude of seismic waves as a function of charge quantity, Q [after LEVYANT 1964]. H_q – charge depth; h_o – thickness of low-velocity layer

1. ábra. A szeizmikus hullámok amplitúdója a Q töltetnagyság függvényében [LEVYANT 1964 után]. H_Q – töltetmélység; h_o – lazaréteg vastagsága

Рис. 1. Амплитуды сейсмических волн в зависимости от величины заряда Q [по ЛЕВЯНТУ 1964].
H_q – глубина заряда; h_o – мощность зоны малых скоростей

3. Graphic representation of the frequency effect

There is no prospect of solving the problem by determining the apparent frequency, f_0, with the aim of establishing a more detailed connection with the quantity of charge. The reason is that while the apparent frequency is of interest for the purpose of wave correlation and interpretation, there should be different changes caused in the specific frequency components by varying the quantity of the charge, and these can therefore be demonstrated only in the amplitude–frequency spectrum. An example of this is shown in *Fig. 2.* A good survey results from the direct comparison of spectra for various distances from the shotpoint and for individual time windows which contain different waves. It is obvious that the higher frequency portions increase as the quantity of the charge is reduced. It is conspicuous especially for the reflected waves that while the maxima change their amplitude systematically, their frequency remains stable. This applies, however, only to one reception range (x, t) each where the geophones, ground coupling, wave paths and reflection effects remained unchanged throughout the series of experiments. When, however, a comparison is made of the spectra of the reflected waves in the two different reception ranges, the position and form of the individual maxima will be found to differ considerably. This suggests the need for a representation or calculating technique from which these effects which have been caused by wave propagation and reception, are eliminated.

Normalized spectra are compared in Fig. 2; absolute spectra are shown in *Fig. 3* that refer to the same (x, t) range as those in the centre column in Fig. 2. It is clearly demonstrated that the decrease in the amplitudes intensifies toward the higher frequencies as the quantity of charge grows, whereas it is hardly present in the frequency interval covered for which the charges are very small (e.g. two caps). The idea which suggests itself first is to try and generalize this amplitude change in the form of a simple envelope curve. It is not practical, however, because the effects from wave propagation and reception are still too strong.

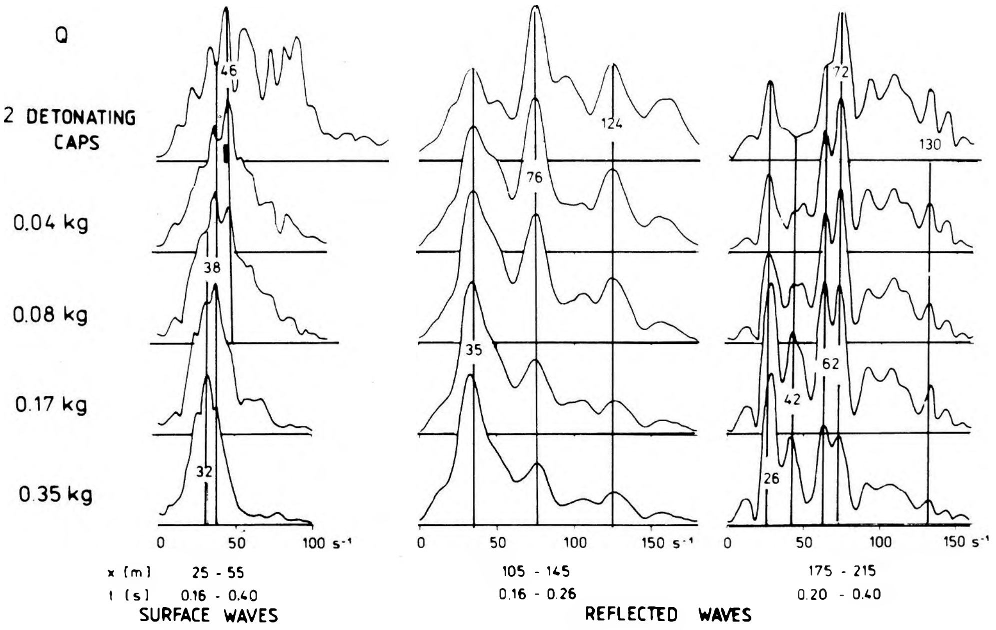

Fig. 2. Amplitude–frequency spectra for variations of charge quantity, Q, and for different distances x from the shot point and different time intervals Δt. Charge depth: 15 m, closely below low-velocity layer

2. ábra. Amplitúdó–frekvencia spektrumok változó Q töltetnagyságra és különböző x robbantópont távolságokra, különböző Δt időablakokban. Töltetmélység: 15 m, közvetlenül a lazaréteg talpa alatt

Рис. 2. Амплитуды–частотные спектры при разных величинах заряда Q и расстояний между пунктом взрыва и пунктом приема в разных временных окнах. Глубина заряда 15 м, непосредственно под зоной малых скоростей

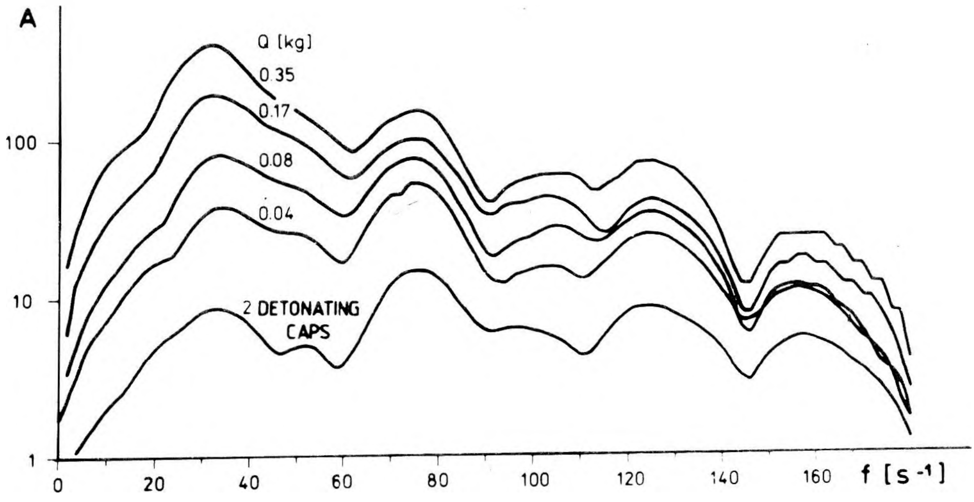

Fig. 3. Absolute amplitude spectra for different charge quantities, Q (for data, see Fig. 2, centre column)

3. ábra. Különböző Q töltetnagyságokhoz tartozó abszolút amplitúdóspektrumok (adatok, mint a 2. ábra középső oszlopában)

Рис. 3. Абсолютные амплитудные спектры, относящиеся в разным величинам заряда Q (данные также как в среднем столбце, рис. 2)

As a next step one may try to show the spectral amplitude response separately for the individual frequency components as a function of the quantity of the charge. *Fig. 4* indicates that this appears to be a good approach to quantifying the relation between the quantity of the charge and the frequency. At low frequencies the amplitudes increase with the quantity of the charge and then decrease from about 30 Hz onward. This decrease is greatest at about 40 Hz and then diminishes with increasing frequency. There is the same trend for all three reception ranges analysed, with regard both to surface waves and reflected waves, and the predominant effect of wave propagation and reception has been eliminated.

When one changes over now to the amplitudes of the absolute spectra and selects a double logarithmic scale, a type of representation results which was once tried by MOLOTOVA [1964] but has not been used since *(Fig. 5)*. It can provide p values for each frequency interval and each individual frequency component, which then serve as a measure of changes in the spectral amplitude portion as a function of the quantity of the charge. When the p values found in this manner are summarized as a function of frequency, this should give a suitable approach to determining charge quantity–frequency relations. This should make it possible to compare quantitatively the different excitation conditions such as the depth of the charge, the surrounding rock and the type of explosive.

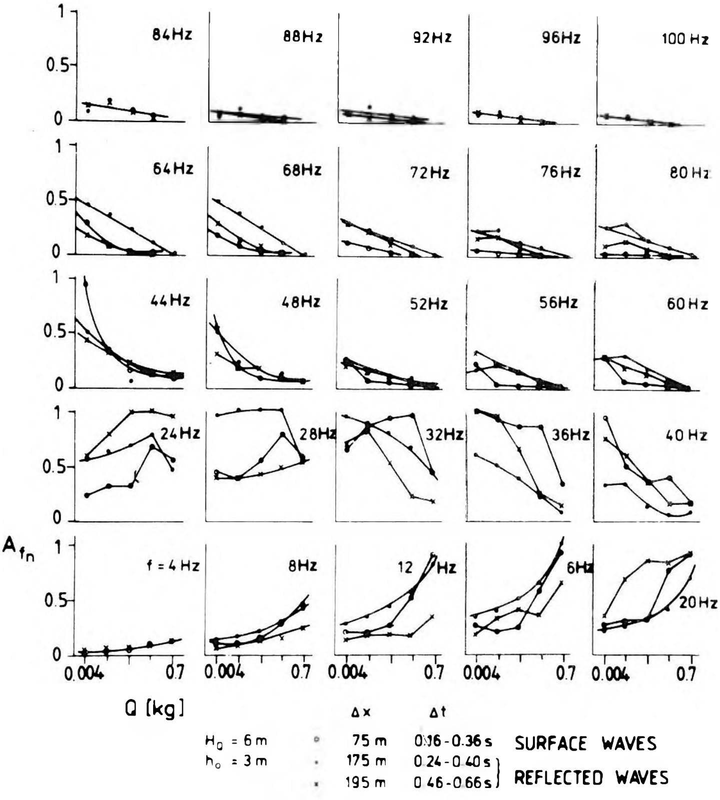

Fig. 4. Amplitudes of normalized spectra as a function of charge quantity, Q, for individual frequency components (for data see Fig. 2)
H_Q – charge depth; h_o – thickness of low-velocity layer

4. ábra. Normált amplitúdóspektrumok a Q töltetnagyság függvényében, kiválasztott frekvencia komponensekre. H_Q – töltetmélység; h_o – lazaréteg vastagsága (adatok, mint a 2. ábrán)

Рис. 4. Нормализованные амплитудные спектры на выбранные компоненты частот в зависимости от величины заряда.
H_Q – глубина заряда; h_o – мощность зоны малых скоростей (данные также как в рис. 2)

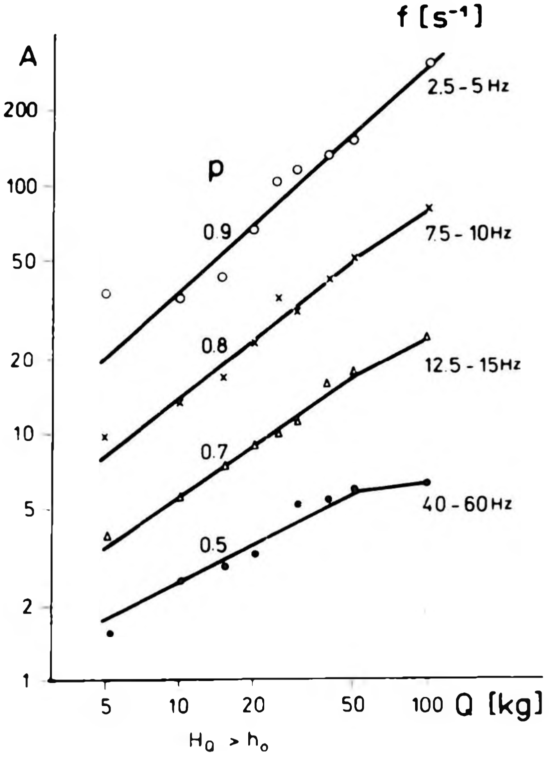

Fig. 5. Amplitudes of seismic waves as a function of charge quantity, Q, for different frequency intervals [after MOLOTOVA 1964].
H_Q – charge depth; h_o – thickness of low-velocity layer

5. ábra. A szeizmikus hullámok amplitúdói a Q töltetnagyság függvényében, különböző frekvencia-intervallumokban [MOLOTOVA 1964 után]
H_Q – töltetmélység; h_o – lazaréteg vastagsága

Рис. 5. Амплитуды сейсмических волн в разных частотных интервалах в зависимости от величины заряда [по МОЛОТОВОЙ 1964].
H_Q – глубина заряда; h_o – мощность зоны малых скоростей

4. A graphical-numerical method

In a relation

$$A(Q, f) = kQ^{p(f)}$$

or

$$\lg A_{f_i}(Q) = \lg k + (\lg Q)\,(p_{f_i})$$

the following applies to each frequency component of the spectrum:

$$p_{f_i} = \frac{\lg A_{f_i, Q_2} - \lg A_{f_i, Q_1}}{lg\, Q_2 - lg\, Q_1}$$

In this way the p_{f_i} values can be determined from the inclination of straight lines. For a sufficiently safe determination of the inclination of the straight line it is useful to have readings available for several (at least four) different charge quantities. The individual charges in a series of experiments should differ by a factor of two each. Figs. 6–8 demonstrate how such a series of experiments is evaluated.

Fig. 6 shows the spectral amplitudes derived from the absolute amplitude spectra, as a function of the quantity of the charge. As can be seen, the relevant readings can be summarized to give straight lines. The p_{f_i} determined from these are plotted on the r.h. side of Fig. 6. From this series of data it is already clear that a systematic connection should exist between p and f.

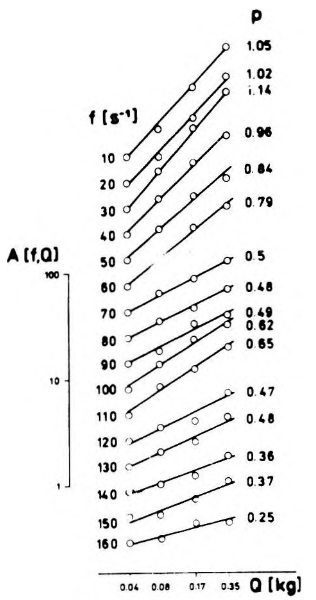

Fig. 6. Spectral amplitudes of reflected waves as a function of charge quantity for determining exponent p (for data, see Fig. 2, centre column)

6. ábra. Reflektált hullámok spektrum-amplitúdói a töltetnagyság függvényében a p kitevő meghatározására (adatok, mint a 2. ábra középső oszlopában)

Рис. 6. Спектральные амплитуды отраженных волн, в зависимости от величины заряда для определения показателя «p». (Данные также как в среднем столбце рис. 2)

When these p_{f_i} values are plotted against the frequency, the result provides the desired quantitative relation. For example, *Fig. 7* summarizes the p values of Fig. 6. The reduction of p with increasing frequency which has been previously detected in a qualitative sense, is now quite obvious. Now the attempt can be made to determine an approximate function, in this case a straight line

$$p = a - bf$$

where the constants a and b are the desired comparative values which indicate the change in the spectral amplitudes when the quantity of the charge varies (f denotes frequency). The only remaining effects on these constants are essentially the surrounding rock and the depth of the charge.

This statement must, however, be qualified in one respect. As has been said, some workers report that the exponent p in the relation $A = kQ^p$ is dependent also on the quantity of the charge in cases where the charge quantity interval under consideration is quite large (see for example Fig. 1). In these cases p is reduced as the quantity of the charge increases. It therefore appears desirable to define the p values obtained and/or the function $p = f$ (frequency) with its constants determined from these values, only for a specific range of charge quantities that should not be too wide.

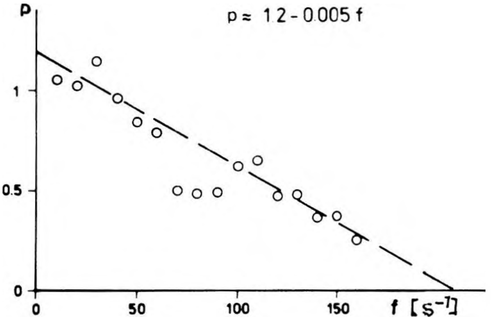

Fig. 7. Exponent p as a function of frequency (values from Fig. 6)

7. ábra. A p kitevő a frekvencia függvényében (a 6. ábráról vett adatok)

Рис. 7. Показатель «p» в завизимости от частот (данные взяты из рис. 6.)

Fig. 8 is intended as an illustration of the fact that the determination of p may be rather difficult. It shows the values for the surface waves from Fig. 2, and there is an obvious difference between these and the reflected waves (Fig. 6). The amplitude curve inclinations can be determined only up to 40 Hz because no straight lines can be formed beyond 50 Hz. In these cases it will not be possible, for the time being, to identify p and, as a result, $p = f$ (frequency). Instead the representation $\lg A = F(\lg Q)$ must be used for assessment and comparison. In this example, reflected waves may possibly have an effect on the data, considering the low charge quantities.

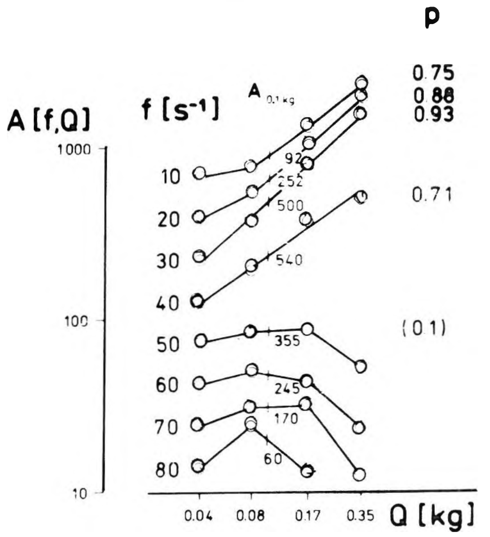

Fig. 8. Spectral amplitudes of surface waves as a function of charge quantity for determining exponent p (for data, see Fig. 2, left column)

8. ábra. Felületi hullámok spektrum-amplitúdói a töltetnagyság függvényében a p kitevő meghatározására (adatok, mint a 2. ábra baloldali oszlopában)

Рис. 8. Спектральные амплитуды поверхностных волн, в зависимости от величины заряда для определения показателя «p». (Данные также как в левом столбце рис. 2)

Finally, mention should be made of another possibility for determining p which can be used when readings are available for only two different charge quantities. An alternative to

$$p_{f_i} = \frac{\lg A_{f_i, Q_2} - \lg A_{f_i, Q_1}}{\lg Q_2 - \lg Q_1}$$

is

$$p_{f_i} = \frac{\lg (A_{Q_2}/A_{Q_1})_{f_i}}{\lg (Q_2/Q_1)}$$

where $(A_{Q_2}/A_{Q_1})_{f_i}$ (in the range $0 \leq f_i \leq$ maximum frequency with an amplitude which can still be evaluated) is the division of the two spectra for Q_2 and Q_1. Since $\lg (Q_2/Q_1)$ is constant here, p can be determined from the spectral division. One should, however, be careful of this kind of determination because the accidental effect from a single shot which is reduced by the formation of straight lines in the event of several charges, may excessively influence the result. An example of this type of determination is given in *Fig. 9*. Here it seems just about possible to eliminate the effect of a connection between p and f (caused by a slight shift in the amplitude maxima of the two spectra), particularly for the higher frequencies. As for the low frequencies, however, the shape of a curve already becomes quite problematic.

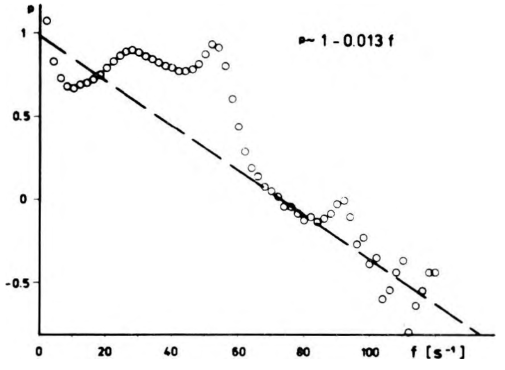

Fig. 9. Exponent p as a function of frequency, determined from spectral division for two charge quantities ($Q_2=0.17$ kg, $Q_1=0.04$ kg)

9. ábra. A p kitevő a frekvencia függvényében, két töltetnagysághoz tartozó spektrum hányadosából meghatározva ($Q_2=0,17$ kg, $Q_1=0,04$ kg)

Рис. 9. Показатель «p» в зависимости от частоты, определяемый делением спектров, относящихся к двум величинам заряда ($Q_2=0,17$ кг, $Q_1=0,04$ кг)

5. Preliminary results

The following data have so far resulted from an analysis of charge quantity tests for the Cenozoic:

Area	Q(kg)	H_Q(m)	h_0(m)	Wave type	a	b
1	0.04 – 0.35	15	14	reflected	1.2 1.15	0.005 0.005
		5	14	reflected	1.0 1.1	0.013 0.01
2	0.04 – 0.7	18	15	reflected	1.25	0.004
		6	15	reflected surface wave	1.7 2.3 1.8	0.008 0.027 0.023
3	0.04 – 0.17	24	21.5	reflected	1.7	0.01
		6	21.5	reflected	2.0	0.016

This makes it possible to estimate quantitatively the effect of the charge quantity on the frequency content of seismic waves for an area studied and under the measuring conditions selected. For example, the following can be concluded for area 1:

The constants a and b are

for shooting below the low-velocity layer (LVL) $a=1$, $b=0.005$

for shooting in the low-velocity layer $a=1$, $b=0.01$.

From this it follows for shooting	in the LVL	below the LVL
$A \sim Q^1$ for frequencies around	0–20 Hz	0–40 Hz
$A \sim Q^{1/2}$	40–60 Hz	80–120 Hz
$A \sim Q^0 = \text{const.}$	80–120 Hz	180–220 Hz
$A \sim Q^{-1/2}$	150 Hz	300 Hz

This means that in the case of shooting in the low-velocity layer any growth of the charge quantity in the normalized amplitude spectrum causes a reduction of the higher frequency portions which is double that for shooting below the LVL. Or, conversely, any reduction of the charge quantity will roughly raise the higher frequencies in the normalized amplitude spectrum twice as much if the charge is exploded immediately in the low-velocity layer, compared with an explosion below the LVL. The decisive factor for the measuring quality and for approaching geological projects in these cases therefore consists of finding a charge quantity which is just about sufficient.

6. Concluding remarks

In the three areas studied, the relation $p = a - bf$ (see table) which has been obtained is an adequate approximation for describing the dependence of the spectral amplitude behaviour on the quantity of the charge. In area 3 it is suggested that this dependence can also be expressed by the relation $p = a - bf^q$ $(1 < q < 2)$. This is why the results presented here are intended only as examples whose applicability is restricted to the particular area being studied. Regardless of the type of this relation, however, the determination method used, and the quantifiable statement in comparing different excitation parameters, are generally practicable.

REFERENCES

Farr J. B. 1976: Very high resolution seismic profiling. 38th EAEG Meeting, The Hague, Preprint

Gaertner H., Rische H., Fischer K. H. 1985: Schusseismische Braunkohlenerkundung als Alternativlösung. Zeitschr. f. Geol. Wissensch. **13**, 1, pp. 23–32

Levyant V. B. 1964: On the effectiveness of near-surface explosions for seismic measurements (a case history of the Volgograd area (in Russian). Geol. i razv. 10, pp. 123–140

Meissner R., Stegena L. 1977: Praxis der seismischen Feldmessung und Auswertung. Akadémiai Kiadó, Budapest

MOLOTOVA, L. V. 1964: On the influence of explosion conditions on the frequency spectra of seismic waves. I. Results of experimental measurements (in Russian). Izv. A.N. SSSR, Ser. geof., 12, pp. 1753–1766

RISCHE H. 1985: Anregung seismischer Wellen in sehr geringen Tiefen. Geophysik und Geologie, 3, 2, pp. 125–136

ZIOLKOWSKI A., LERWILL W. E. 1979: A simple approach to high-resolution seismic profiling for coal. Geophysical Prospecting **27**, 2, pp. 360–393

SZEIZMIKUS HULLÁMOK FREKVENCIA-TARTALMÁNAK FÜGGÉSE A TÖLTETNAGYSÁGTÓL

Hans RISCHE

A töltetnagyság – frekvencia-tartalom összefüggés vizsgálatára végzett kísérleti mérések során az ismert $A = kQ^p$ összefüggést ellenőrizték és egy jobb, $p = a - b \cdot$ frekvencia kapcsolatot határozták meg. Ez az egyenlet megfelelő pontossággal közelíti az amplitúdóspektrum töltetnagyságtól való függését.

ЗАВИСИМОСТЬ ЧАСТОТЫ СЕЙСМИЧЕСКИХ ВОЛН ОТ ВЕЛИЧИНЫ ЗАРЯДА

Ганс РИШЕ

При проведении опытных измерений с целью изучения зависимости частоты от величины заряда проверялась известная зависимость $A = kQ^p$ и определялась более точная связ: $a - bf$. Это новое уравнение достаточной точностью приближает зависимость амплитудного спектра от величины заряда.