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The effect of sweep signal parameters on correlation wavelet

Sweep sinyali parametrelerinin korelasyon dalgacığı üzerindeki etkileri

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ABSTRACT

Vibroseis is an important seismic exploration method whose sweep signal parameters vary with rock layers deep in the earth. Controlling of sweep signal frequency band is extremely useful method in vibroseis data acquisition. The vibrator is a controlled energy source employed in seismic methods. Nowadays it is widely used and preferable seismic source for land seismic exploration. Suitable input signal is typically a sinusoid that changes frequency within a bandwidth. To obtain high-quality subsurface images, amplitude of the sweep signal and Klauder wavelet is important parameter of vibroseis.

In this study, amplitude of Klauder wavelet variations with respect to different sweep parameters are investigated; tests have been made based on a variety of sweep numbers, sweep length, peak force ratio and sweep bandwidth. The results have been compared with theoretical values and the tested parameters are evaluated in the shot and processing domain.

Keywords: Sweep, Number of sweep, Sweep length, Peak force, Number of vibrator, Sweep bandwidth.

ÖZ

Vibrosismik, sismik aramaların önemli bir yöntemi olup, uygulanan sweep sinyalinin

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parametreleri yerin derinliklerindeki kaya katmanları ile değişir. Vibrosismik'te sismik verinin frekans aralığının kontrol edilebilmesi son derece faydalıdır. Vibratör, sismik yöntemlerde kullanılan kontrollü bir enerji kaynağıdır. Günümüzde vibrosismik karada yapılan sismik arama çalışmalarında en çok kullanılan ve tercih edilen sismik enerji kaynağıdır. Uygun giriş sinyali, frekansı bir frekans band genişliği içinde değişen sinüzoidal dalga formundadır. Yüksek ayrımlılık ile yeraltı görüntüleri elde etmek için, sweep sinyalinin genliği ve Klauder dalgacığının genliği vibrosismiğin önemli parametreleridir.

Bu çalışmada, farklı sweep parametrelerine göre Klauder dalgacık genliğinin değişimleri araştırılmıştır. Testlerde çeşitli sweep sayıları, sweep uzunluğu, pik kuvveti oranı ve sweep band genişliği temel alınarak yapılmıştır. Sonuçlar teorik değerlerle karşılaştırılmış olup, test edilen parametreler atış ve veri işlem aşamalarında değerlendirilmiştir.

Anahtar kelimeler: *Sweep, Sweep sayısı, Sweep uzunluğu, Pik kuvveti, Vibrator sayısı, Sweep band genişliği.*

INTRODUCTION

Geology of The Survey Area

The province of Osmaniye is located in the East of the Mediterranean Region of Turkey. Also, it is in the Çukurova region and situated between 35° 52' and 36° 42' East Longitudes, 36° 57' and 37° 45' North Latitudes. Figure 1a shows the simplified geology of the vicinity of Osmaniye (Yildiz et al., 2003). Osmaniye region is one of the interesting aspects of Toros Mountains as it has rock-stratigraphical units, which represent the all systems of Cambrian-Tertiary range. The stratigraphy of the Osmaniye province and the area around it presents units starting from the Lower Paleozoic continuing to Late Cretaceous, Eocene and Plio-Quaternary. The rocks of the Middle-Late Devonian age, which constitutes the lower level of Paleozoic units are composed of coral limestones, sandstones and siltstone-shales. Carbonates and ophiolitic complexes appear in Mesozoic units (Ugur et al., 2012).

Field test records have been acquired over the alluvial areas which were of Holocene age, because the vibrators were imparted sweep signal into the earth very easily in the alluvial covered areas.

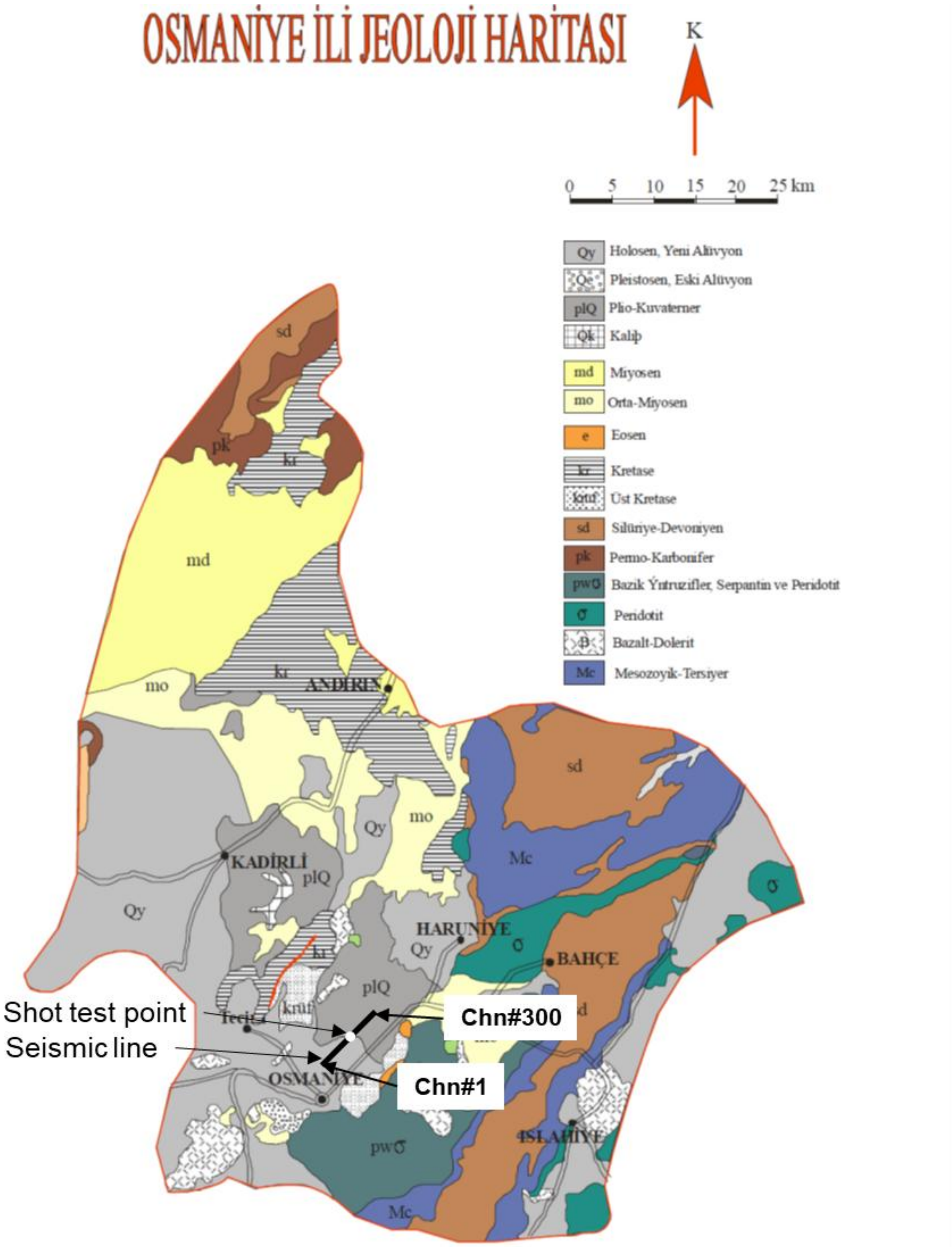

Figure 1a. The simplified geology map of Osmaniye (revised from the geology of Turkey map, MTA, Ugur et al., 2012).

Şekil 1a. Osmaniye İli jeoloji haritası (MTA Türkiye jeoloji haritasından sadeleştirilmiştir, Ugur et al., 2012*).*

Theory

The technique consists essentially of the following steps: (Figure 1b) A frequency-modulated, sinusoidal, sweep signal or control signal is transmitted by radio from the recording truck to the vibrators. Each vibrator, hydraulically driven and controlled by this electrical signal, exerts a quasi-sinusoidal force of many tons on the ground surface, generating seismic waves. The peak force is limited by the weight used to hold the vibrator in contact with the earth. An electrical feedback system keeps the ground motion in unison with the control signal. Recorded seismic signals from a vibrator are a superposition of long wave trains arriving at different times and do not resemble a normal seismogram (Seriff and Kim, 1970).

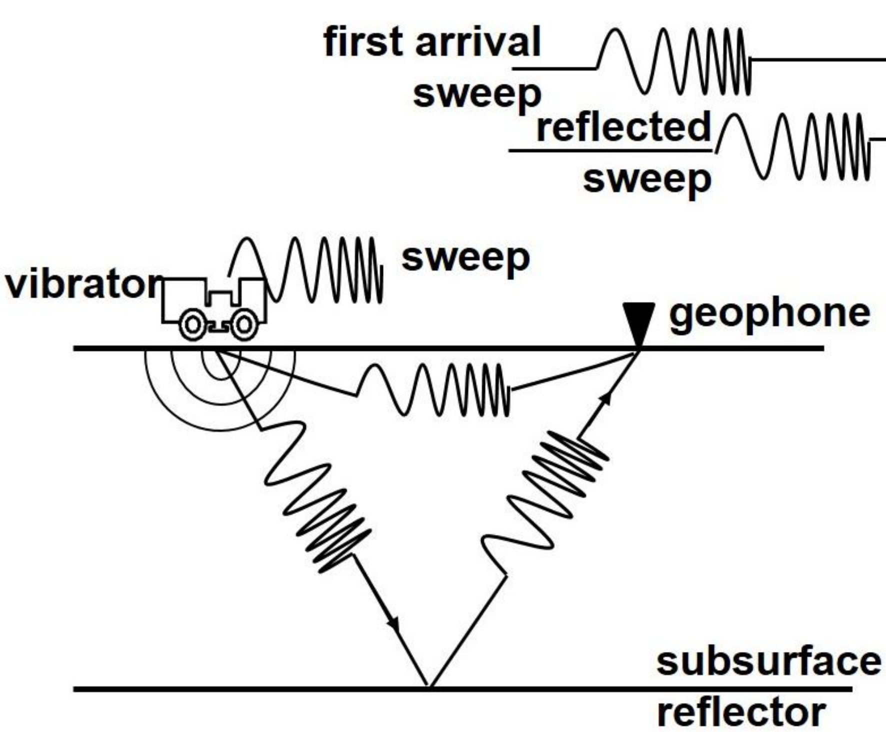

Figure 1b. Schematic view of vibroseismic technique (revised from Crawford et al., 1960; Seriff and Kim, 1970; Chapman et al., 1981 and Pann, 1986).

Şekil 1b. Vibrosismik yöntemin şematik görünüşü (Crawford et al., 1960; Seriff and Kim, 1970; Chapman et al., 1981 ve Pann, 1986'den revize edildi).

The basic principle of the vibroseis system can be explained as pointed out by Geyer (1970) is:

1- An input pilot signal in the form of a sweep-frequency sinusoid is transmitted into the earth where it is convolved with the reflection coefficients distribution,

2- Reflected signals are cross-correlated with the input signal to obtain the output data.

Mathematical description of the received output at the earth surface, with vibrator as energy source, (Cunningham, 1979) is summarized in Appendix. The sweep frequency range is designed to obtain the highest reflection signal to noise ratio. The vibroseis sweep is programmed to transmit a broad range of frequencies. Shallow reflectors may reflect a broad bandwidth containing high frequencies as well as low frequencies. Generally deeper reflectors do not appear with the return high frequencies because of absorption of the high frequency components of the signal by the near surface. To mitigate the higher frequency absorption, the amplitudes of higher sweep frequencies must be increased.

The sweep representation is investigated by Klauder et al. (1960); Geyer (1970) and Cunningham (1979). Linear sweep-frequency sinusoid wave $s(t)$ can be given as

$$s(t) = E\sin 2\pi\left(f_o + \frac{kt}{2}\right)t . \quad \text{for } 0 \le t \le T \tag{1}$$

or it is also investigated by Seriff and Kim (1970); Goupillaud (1976); Rietsch (1977, 1981); Pelton (1979); Thomas and Heath (1985); Anstey (1991); Li et al. (1995); Sallas et al. (1998) and Chiu et al. (2005). Linear sweep-frequency sinusoidal wave $s(t)$ can be given as

$$s(t) = ESin 2\pi\left[f_1 + \frac{kt}{2}\right]t . \text{ for } 0 \le t \le T \tag{2}$$

according to the definition of the slope frequency

where

E ; signal (sweep) amplitude

f_1 ; start frequency (Hz.)

T ; sweep length (sec)

$k = \frac{f_2 - f_1}{T}$; rate of change per unit time

$f_o = \frac{f_1 + f_2}{2}$; center frequency

f_2 ; end frequency (Hz.).

Eq. (1) and Eq. (2) are linear sweep-frequency sinusoidal wave equation.

The autocorrelation function of the sweep defined with Eq. (A.2) is approximated by Cunningham (1979) as

$$\phi_{ss} = \frac{E^2 T}{2}\frac{\sin \pi(f_2 - f_1)t}{\pi(f_2 - f_1)t}\cos 2\pi\left\{ f_o + \frac{kt}{2}\right\}t . \tag{3}$$

Eq.(3) gives autocorrelation function. In the following, we consider the linear sweep whose instantaneous frequency is a linear function of time in Figure 2a (Sarioglu and Gureli, 2005). In addition, we assume that the sweep has constant amplitude. Figure 2b shows such a sweep (Sarioglu and Gureli, 2005). Combining constant amplitude with linear change of frequency we obtain a flat amplitude spectrum (Figure 2c). Sheriff (1990) defines the Klauder wavelet as the autocorrelation of a linear vibroseis sweep. The autocorrelation of a sweep is equal to a Klauder wavelet. Klauder wavelet of a sweep is shown in Figure 2d.

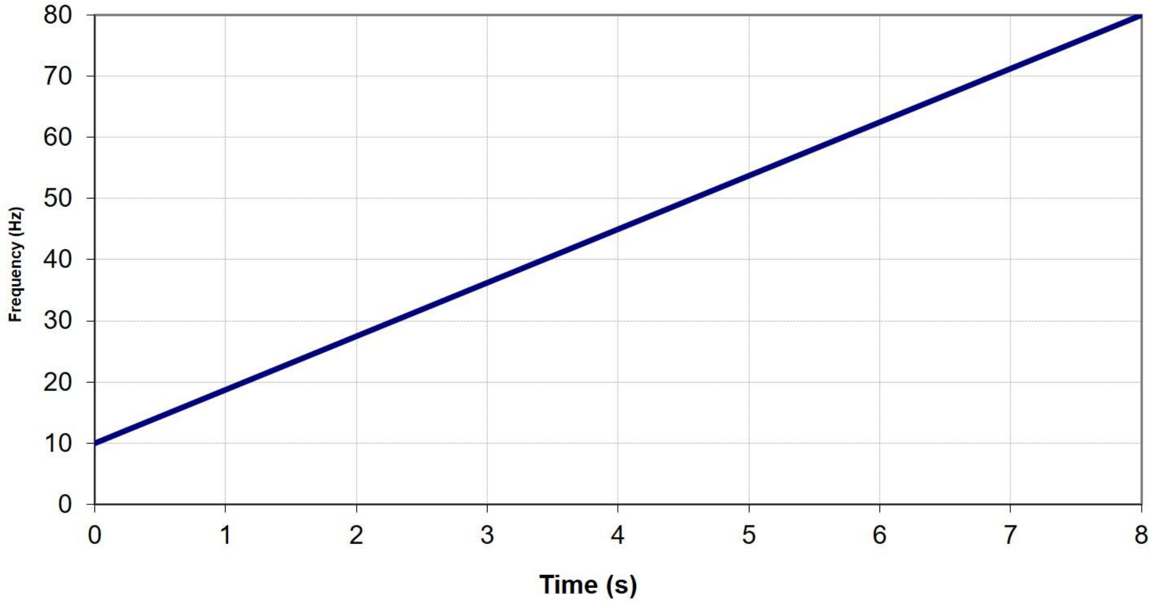

Figure 2a. Frequency-time relation of a linear sweep.

Şekil 2a. Bir lineer sweep'in frekans-zaman ilişkisi.

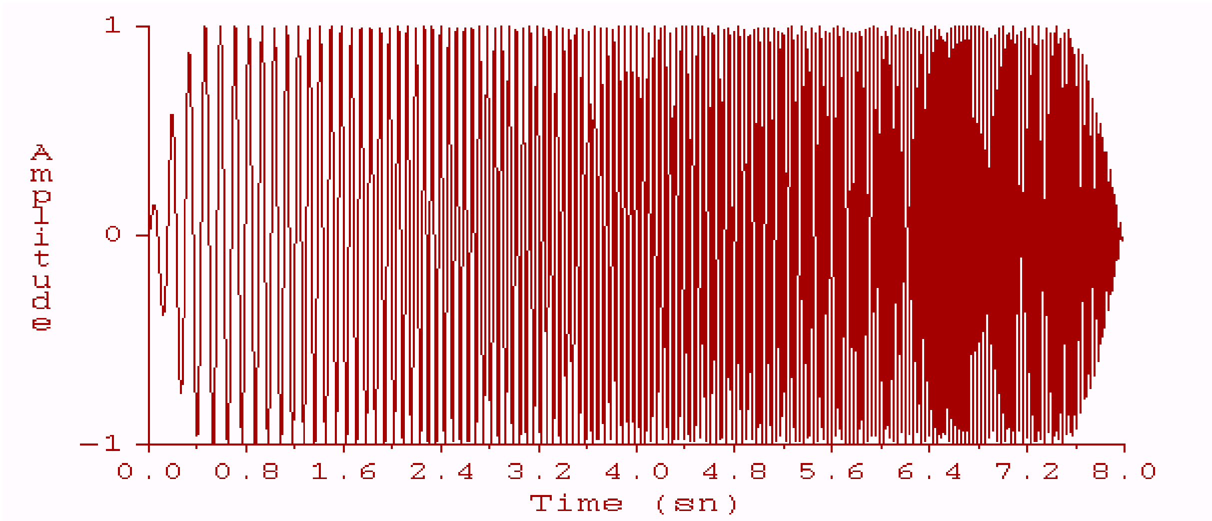

Figure 2b. Linear sweep in the time domain.

Şekil 2b. Lineer sweep'in zaman ortamında görünüşü.

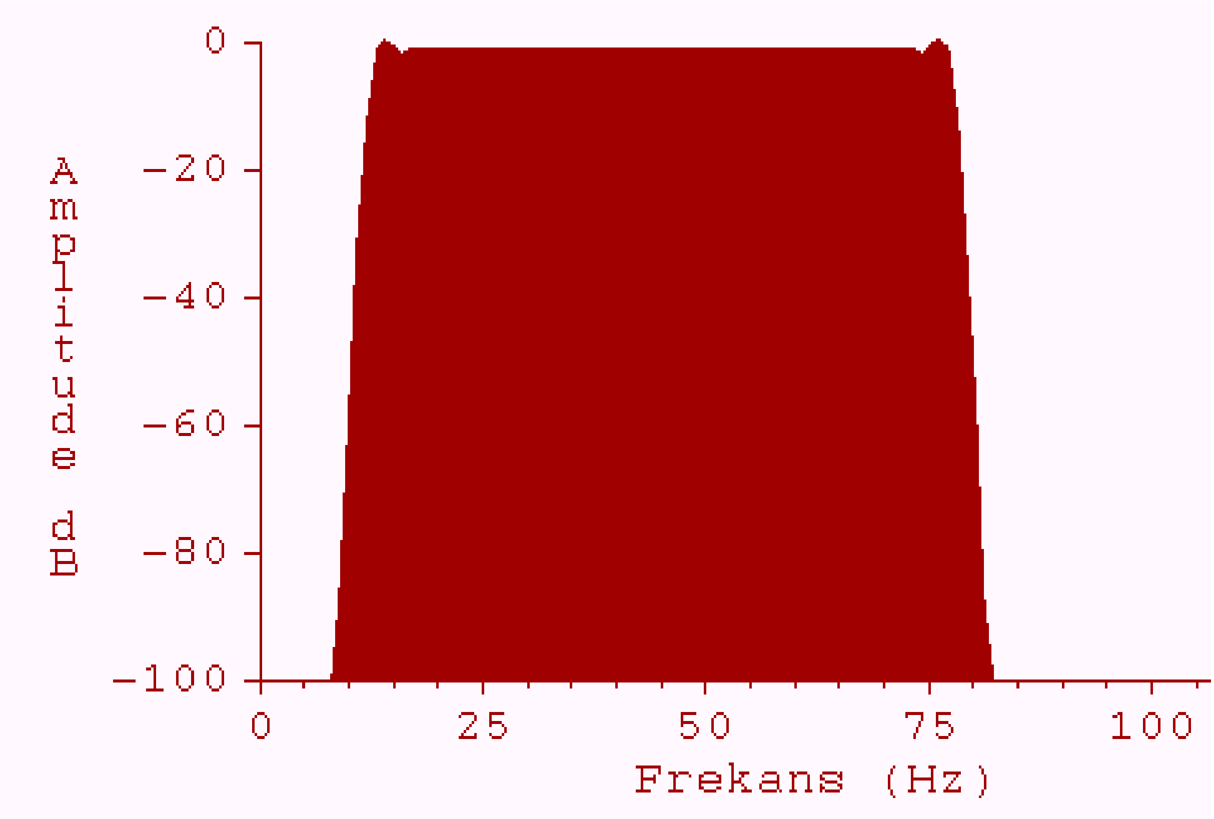

Figure 2c. Linear sweep in the frequency domain.

Şekil 2c. Lineer sweep'in frekans ortamında görünüşü

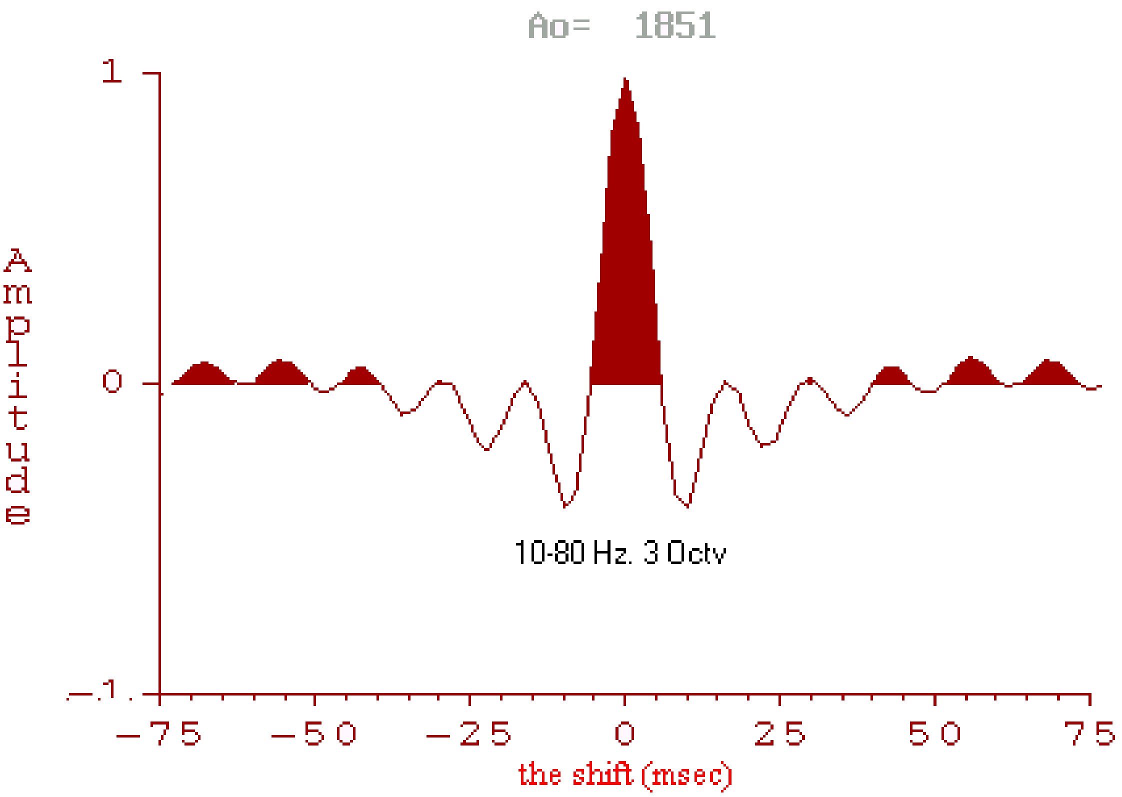

Figure 2d. Autocorrelation of sweep.

Şekil 2d. Sweep'in otokorelasyonu.

Power of amplitude spectrum corresponds to the autocorrelation function (Anstey, 1991), In other words, it represents the energy in the sweep. We are, thus, concerned with the autocorrelation function as far as we deal with the amplitude variation through vibroseis system.

AMPLITUDE VARIATION WITH SWEEP PARAMETERS

Amplitude Variation with Number of Sweep

In vibroseis method, the number of vibrators available is usually fixed, but the only limitation on the number of sweeps per shot point (SP) which is time consuming to record each source point or profile. In Eq. (A.2), if $t=0$ the peak amplitude of autocorrelation is;

$$\phi_{ss}(t=0)=\sum_{\tau=0}^{T} s^2(\tau),$$

$$A=\phi_{ss}(t=0)=A_o. \qquad (4)$$

as shown in Figure 2d. Eq. (4) gives that the peak amplitude value for 1 sweep.

If amplitude of the reference sweep and number of sweeps are, respectively, E and a; amplitude of a times reference sweep is aE and related peak amplitude of autocorrelation is

$$A=\phi_{ss}(t=0)=\sum_{\tau=0}^{T} a^2 s^2(\tau),$$

$$A=\phi_{ss}(t=0)=a^2 A_o. \qquad (5)$$

Eq. (5) says that the amplitude of signal is proportional to the square of sweep number. If the amplitude of autocorrelation of one sweep is A_o, the amplitude of autocorrelation of a sweeps will be $a^2 A_o$ (for correlation after stack), amplitude ratio in term of decibel may be defined as follows

$A=20\log(a^2 A_o / A_o)$ (for correlation after stack),

$A=20\log(aA_o / A_o)$ (for correlation before stack),

The increase in amplitude is

$A=40\log(a)$ dB (for correlation after stack), (6)

$A=20\log(a)$ dB (for correlation before stack), (7)

Eq. (6) and Eq. (7) give the variation of the amplitude of autocorrelation of sweep with the number of sweeps.

Figure 3a shows different autocorrelation wavelets. The amplitude of autocorrelation wavelet is increasing with number of sweeps. Figure 3b shows that the increasing in amplitude is slower at high numbers of sweeps. For example, the increase in amplitude is 12 dB between 1 and 2 sweeps, but the increase in amplitude is 2 dB between 9 and 10 sweeps. 2D shot records are shown with one sweep in Figure 3c, and ten sweeps in Figure 3d. As shown in Figure 3c, amplitude of signal is small and signal to noise ratio is poor. But in Figure 3d, amplitude of signal is bigger and signal to noise ratio is good compared to one sweep record.

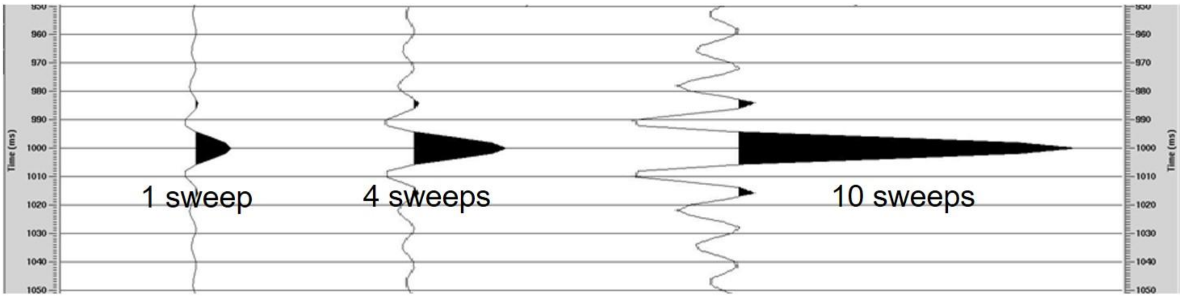

Figure 3a. Autocorrelation wavelets for different number of sweep.

Şekil 3a. Farklı sayıdaki sweep'lerin otokorelasyon dalgacığı.

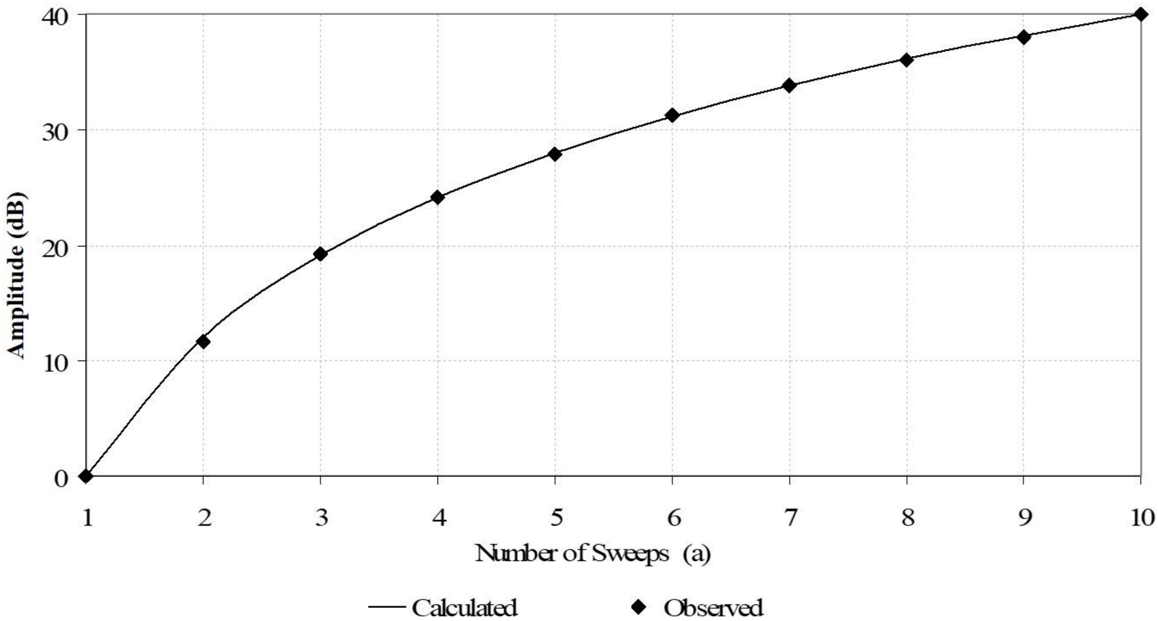

Figure 3b. Variation of peak amplitudes with number of sweep.

Şekil 3b. Pik genliğin sweep sayısı ile değişimi.

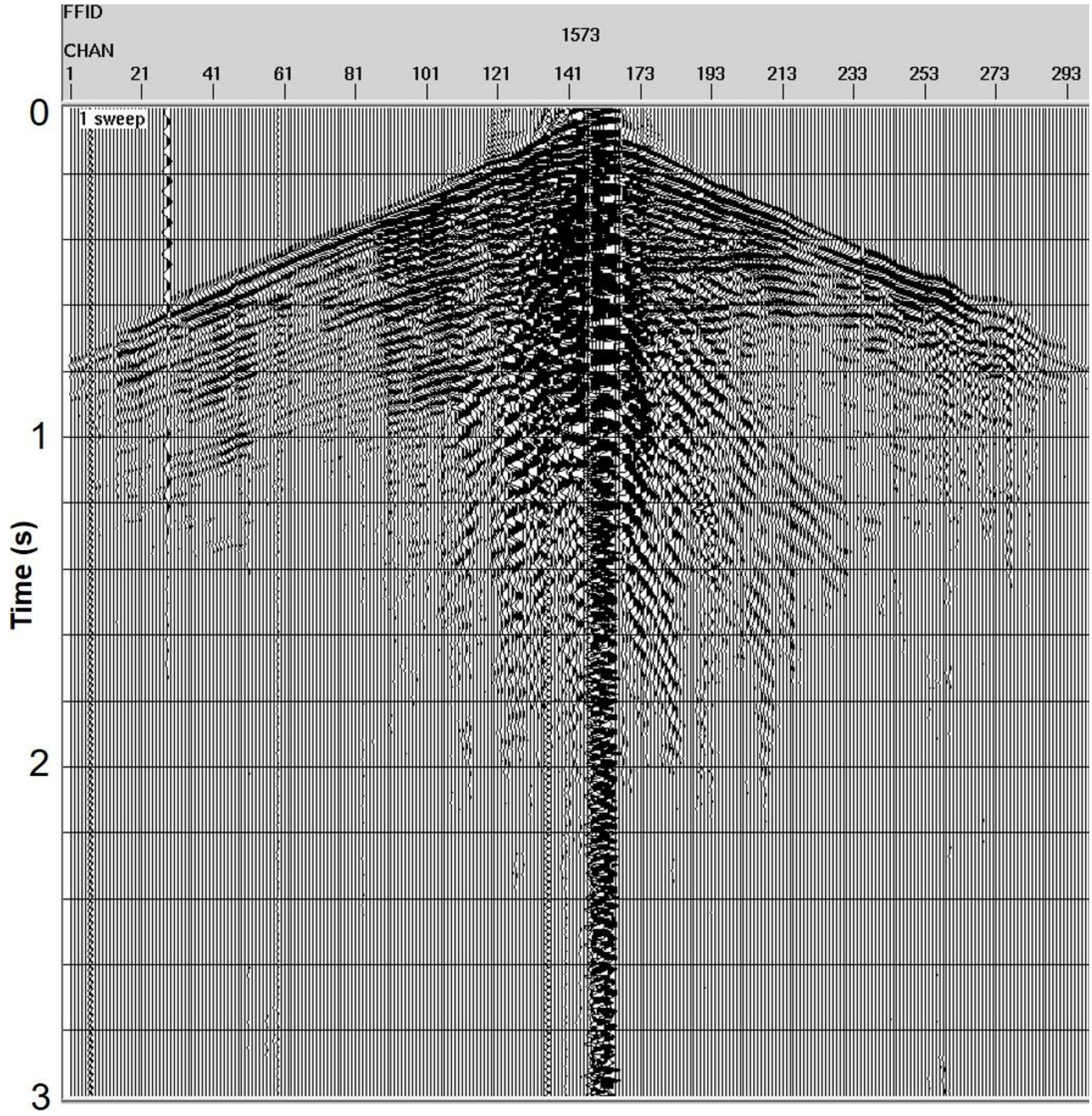

Figure 3c. 2D shot gather with 1 sweep (parameters are 12-64 Hz, 12 sec., Non-Linear -3 dB/Oct., Drive level *80%*, 4 vibrators).

Şekil 3c. 1 sweep ile elde edilmiş 2B atış örneği (Parametreler: 12-64 Hz, 12 sn., Non-Linear -3 dB/Oct., Sürüş seviyesi %80, 4 vibrator).

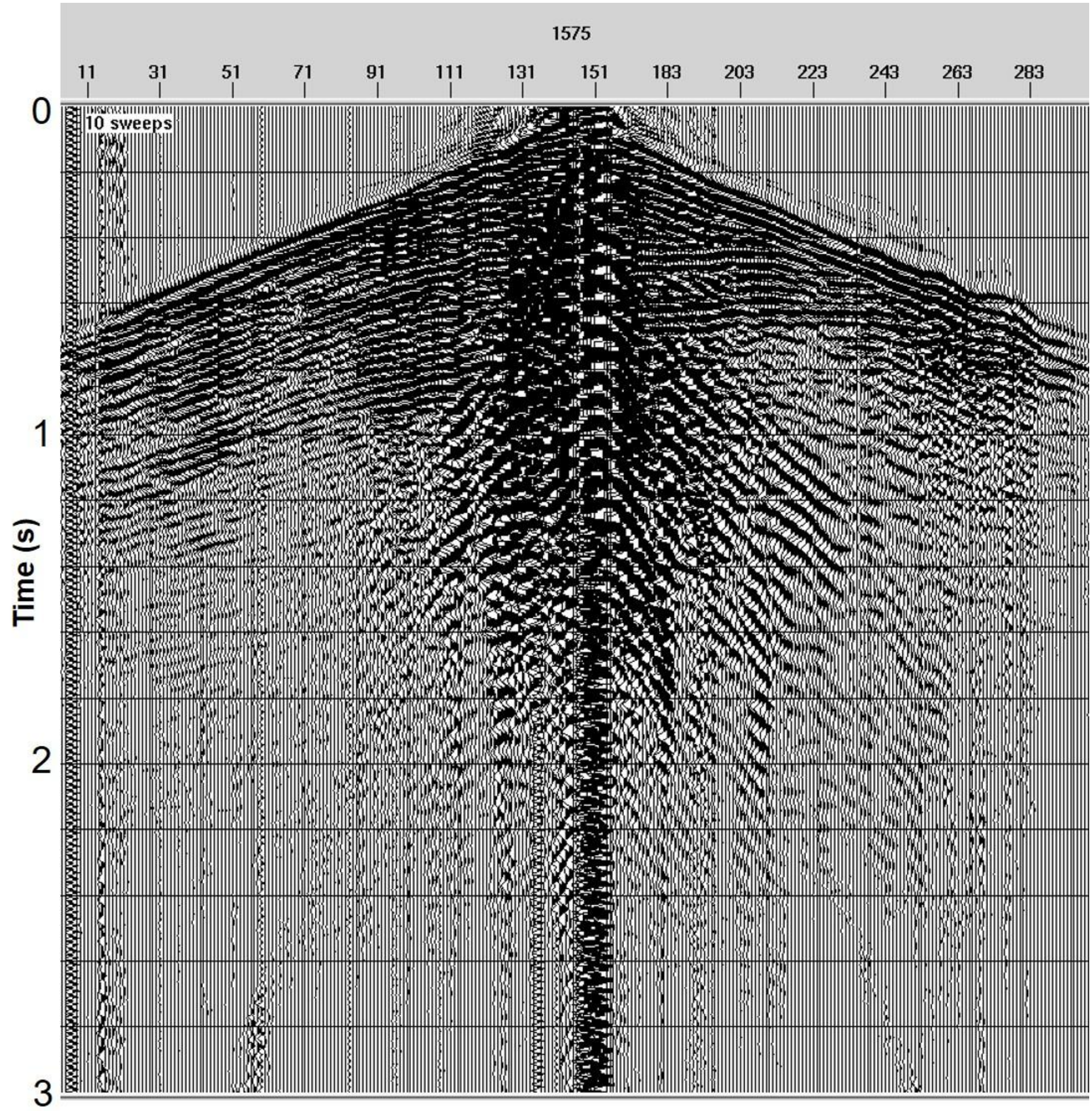

Figure 3d. 2D shot gather with 10 sweeps (parameters are 12-64 Hz, 12 sec., Non-Linear -3 dB/Oct., Drive level *80%*, 4 vibrators).

Şekil 3d. 10 sweep ile elde edilmiş 2B atış örneği (Parametreler: 12-64 Hz, 12 sn., Non-Linear -3 dB/Oct., Sürüş seviyesi %80, 4 vibrator).

As we know, random noises can be suppressed based on the principle of vertical stack by increasing the number of sweep per SP (Xianguo et al., 2006).

Amplitude Variation with Sweep Length

In Eq. (A.2), for sweep length *T=1* sec. the peak amplitude of autocorrelation is

$$\phi_{ss}(t) = \sum_{\tau=0}^{T} s(\tau).s(\tau+t)\,, \qquad (8)$$

$$B = \phi_{ss}(t=0) = B_o\,. \qquad (9)$$

Eq. (8) is an autocorrelation equation. Eq. (9) gives peak amplitude of autocorrelation at zero time.

If the sweep length is $T=b$ sec., the peak amplitude of autocorrelation will be

$$B = \phi_{ss}(t=0) = bB_o\,.$$

The amplitude of wavelet is proportional to the sweep length and B_o which is the peak amplitude of autocorrelation of one-second sweep length.

The gain obtained, in term of decibel, by length multiplication is

$$B = 20\log(bB_o / B_o)\,,$$

$$B = 20\log(b) \quad \text{dB.} \qquad (10)$$

Eq. (10) gives the variation of amplitude of autocorrelation in dB with sweep length. Calculated dB value using b sec sweep length compared with the amplitude of auto-correlated wavelet having one-second duration sweep length is the amount of the amplitude of the auto-correlated wavelet having b sec. sweep length.

Figure 4a shows different autocorrelation wavelets. The amplitude of autocorrelation wavelet is increasing with sweep length. In Figure 4b, the increase in amplitude is faster at short sweeps compared to long sweep. For example, the increase in amplitude is 6 dB between one and two seconds, but the increase in amplitude is 1 dB between 15 and 16 seconds. 2D shot records are shown with 4 seconds sweep length in Figure 4c, and 16 seconds sweep length in Figure 4d. As shown in Figure 4c, amplitude of signal is small and signal to noise ratio is poor. But in Figure 4d, amplitude of signal is bigger and signal to noise ratio is good compare to 4 seconds sweep length record.

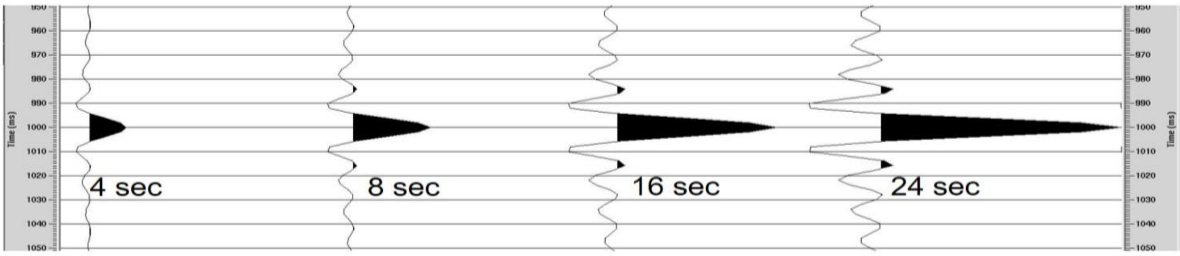

Figure 4a. Autocorrelation wavelets for different sweep length.

Şekil 4a. Farklı uzunluktaki sweep'lerin otokorelasyon dalgacığı.

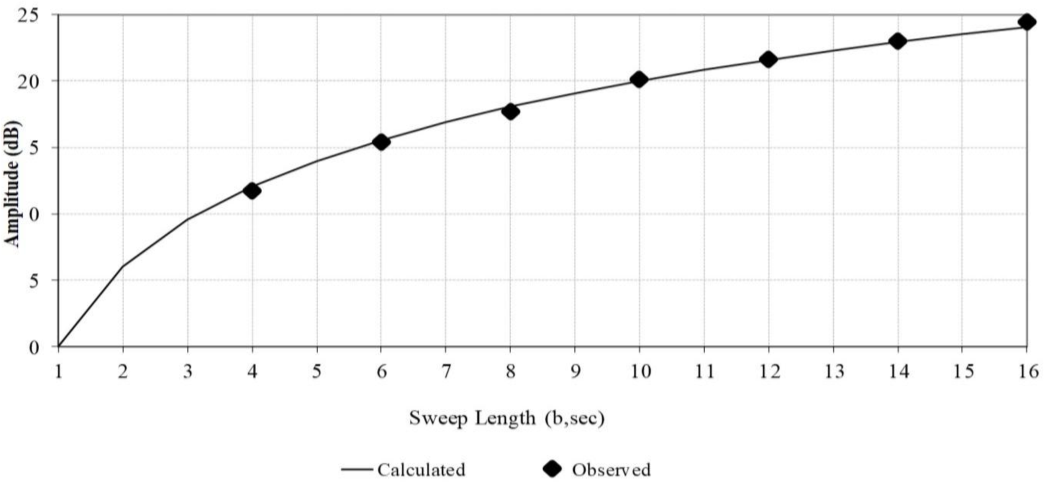

Figure 4b. Variation of peak amplitudes with sweep length.

Şekil 4b. *Pik genliğin sweep uzunluğu ile değişimi.*

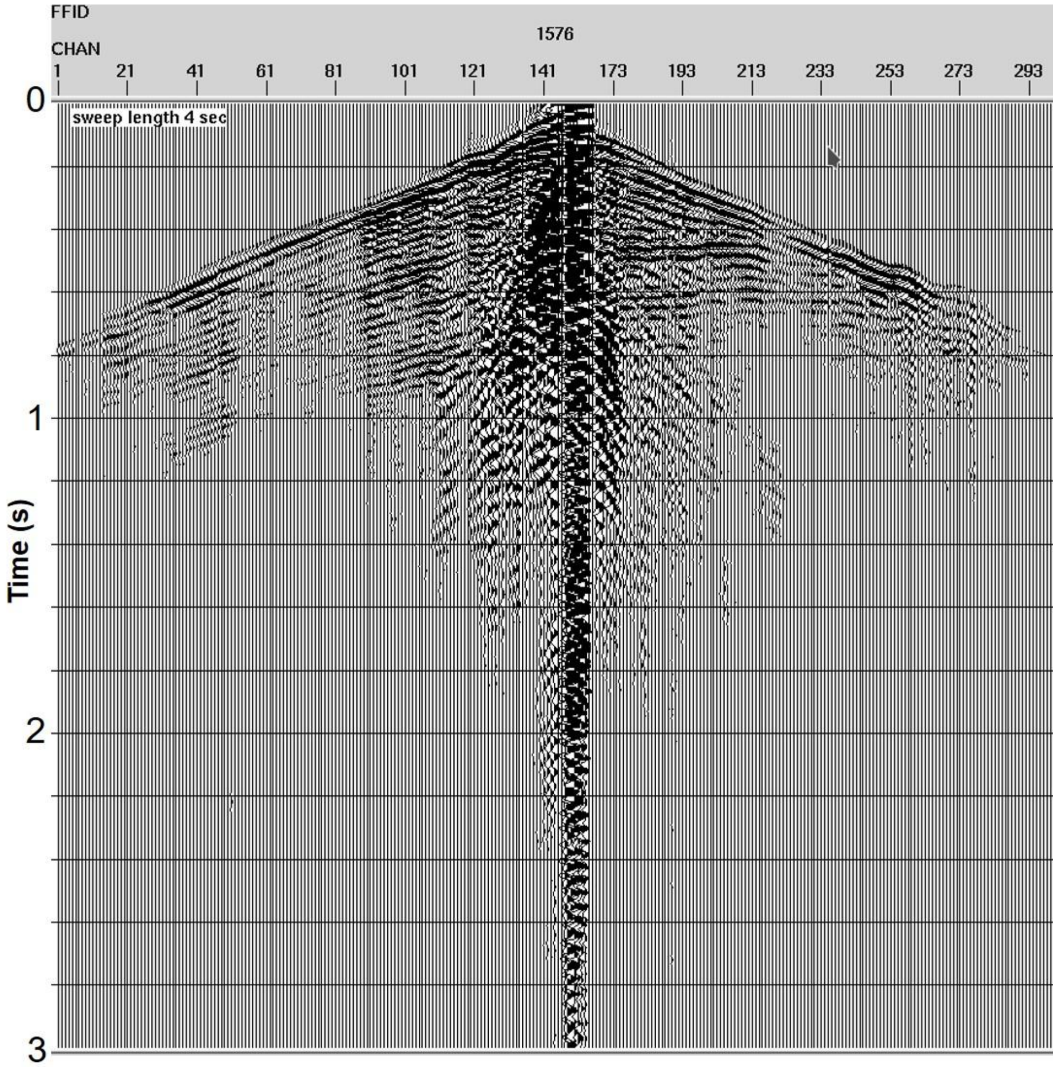

Figure 4c. 2D shot gather with 4 sec sweep length (Parameters are 12-64 Hz, 4 sweeps, Non-Linear -3 dB/Oct., Drive level *80%*, 4 vibrators).

Şekil 4c. 4 sn'lik bir sweep ile elde edilmiş 2B atış örneği. (Parametreler 12-64 Hz, 4 sweep, Non-Linear -3 dB/Oct., Sürüş seviyesi %80, 4 vibrator).

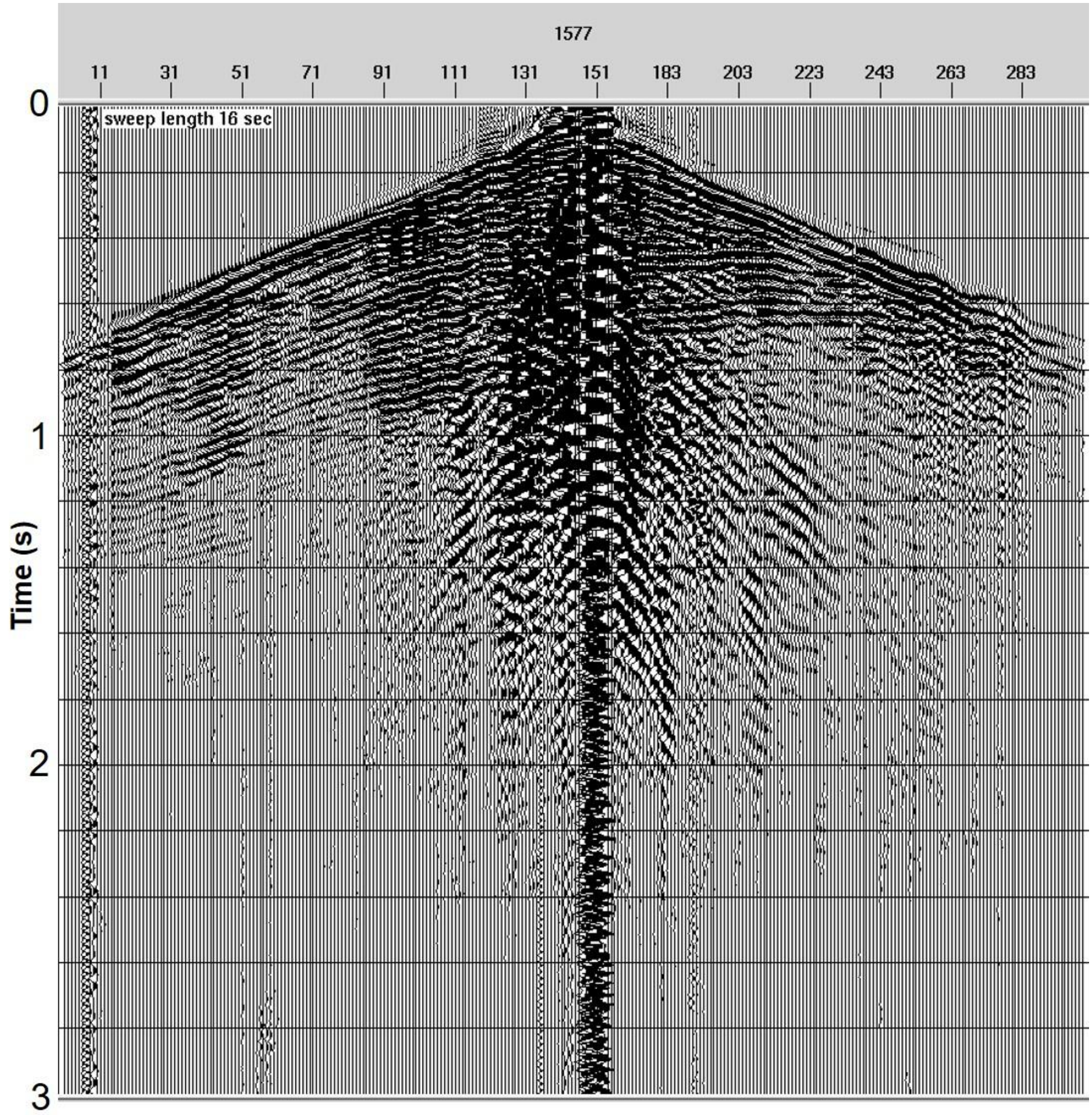

Figure 4d. 2D shot gather with 16 sec sweep length (Parameters are 12-64 Hz, 4 sweeps, Non-Linear -3 dB/Oct., Drive level *80%*, 4 vibrators).

Şekil 4d. 16 sn'lik bir sweep ile elde edilmiş 2B atış örneği. (Parametreler 12-64 Hz., 4 sweep., Non-Linear -3 dB/Oct., Sürüş seviyesi %80, 4 vibrator).

The primary reason for the use of long sweeps is to achieve a reduction in acquisition time. The advantage gained through the use of one long sweep replacing *b* shorter sweeps is the elimination of listen times and system reset times (Lansley, 2009). If total sweep length of b sweeps is equal to one long sweep time, one long sweep will reduce data acquisition time.

Amplitude Variation with Peak-Force

If in Eq.(8), peak force is used as 100%, peak amplitude of autocorrelation of sweep will be

C= $\phi_{ss}(t=0)=C_o$. (11)

Eq. (11) gives peak amplitude of autocorrelation at zero time.

If peak force ratio (Drive level) is c, peak amplitude of autocorrelation of sweep is

$C = \phi_{ss}(t = 0) = cC_o$.

Amplitude ratio in decibel will be

$C = 20\log(cC_o / C_o)$,

The change in amplitude is

$$C = 20\log(c) \text{ dB.} \qquad (12)$$

Eq. (12) gives the variation of amplitude of autocorrelation in dB with peak force. If peak-force can transmit its full force (100%) into the earth, the amplitude of the autocorrelation of the wavelet will be $C_o = 20\log(100/100) = 0$ dB. In other words, there is no variation in term of the amplitude. If the vibrator can transmit 50% of its force into the ground the corresponding amount will be $C = 20\log(50/100) = -6$ dB. This means the amplitude of the auto correlated wavelet decreases 6 dB compared with the previous amplitude.

Figure 5a shows different autocorrelation wavelets. The amplitude of autocorrelation wavelet is increasing with peak force. In Figure 5b, the increasing in amplitude is faster at low force sweeps. But the increase in amplitude is slower at high force sweeps. For example, the increase in amplitude is 6 dB between 5% and 10% peak forces, but the increase in amplitude is 0.5 dB between 95% and 100% peak forces. 2D shot records are shown with 37% peak force in Figure 5c, and 80% peak force in Figure 5d. As shown in Figure 5c, the amplitude of signal is small and signal to noise ratio is poor. But in Figure 5d, the amplitude of signal is bigger and signal to noise ratio is good compared to the 37% peak force record.

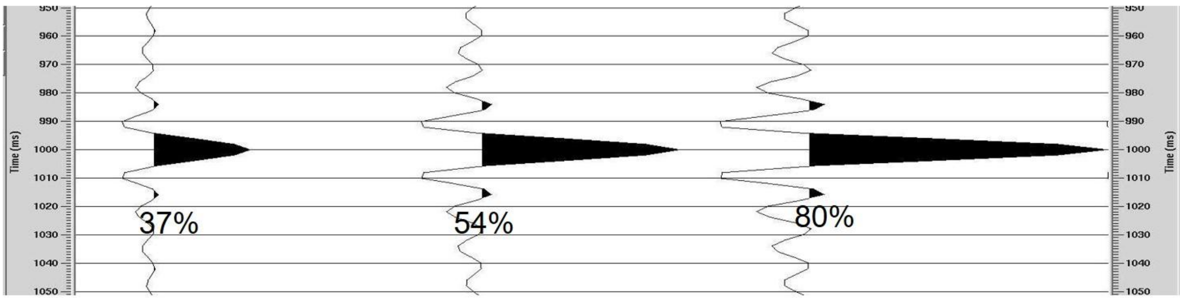

Figure 5a. Autocorrelation wavelets for different peak-force.

Şekil 5a. Farklı sürüş seviyesindeki sweep'lerin otokorelasyon dalgacığı.

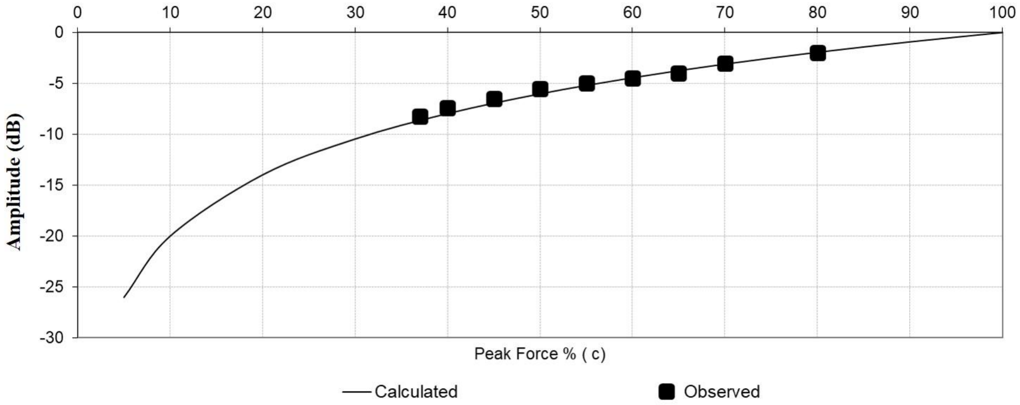

Figure 5b. Variation of peak amplitudes with peak-force.

Şekil 5b. Pik genliğin sürüş seviyesi ile değişimi.

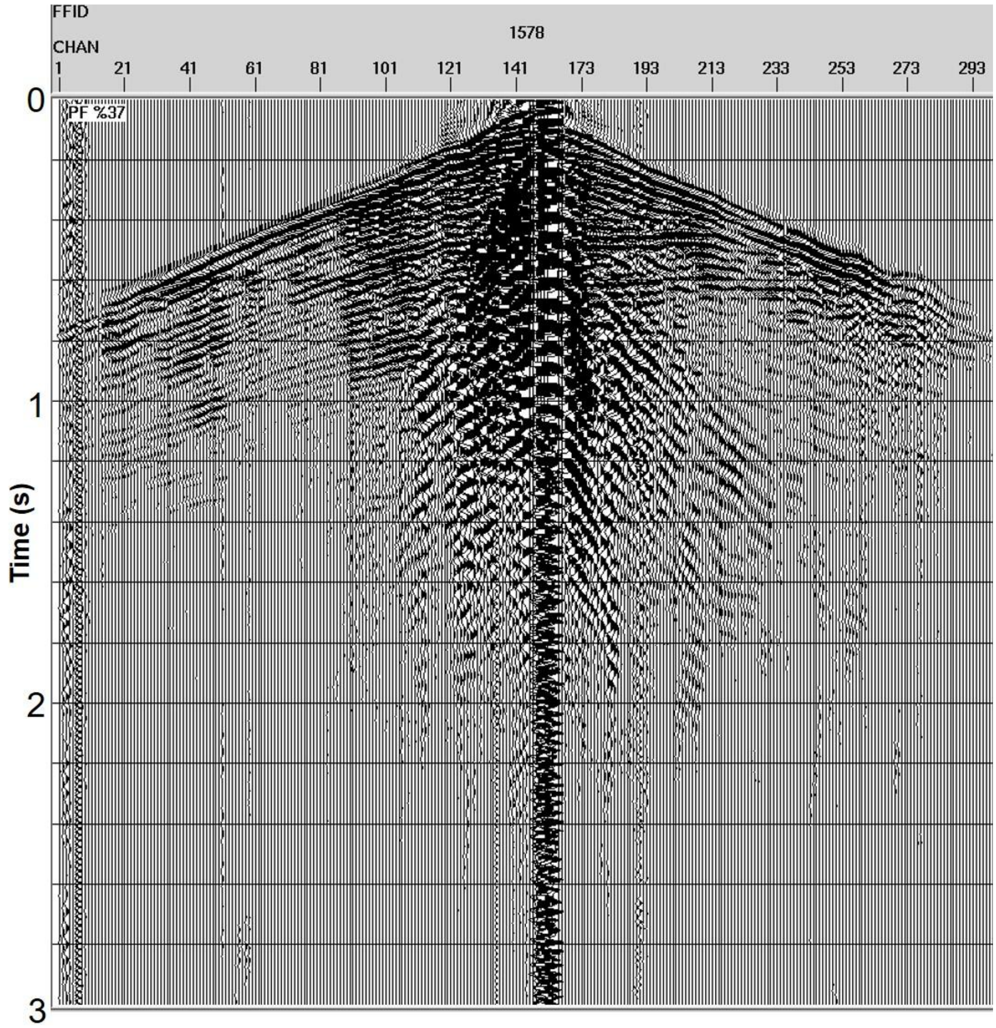

Figure 5c. 2D shot gather with 37% peak-force (Parameters are 12-64 Hz, 4 sweeps, 12 sec, Non-Linear -3 dB/Oct., 4 vibrators).

Şekil 5c. %37'lik sürüş seviyeli bir sweep ile elde edilmiş 2B atış örneği. (Parametreler 12-64 Hz, 4 sweep, 12 sn, Non-Linear -3 dB/Oct., 4 vibrator).

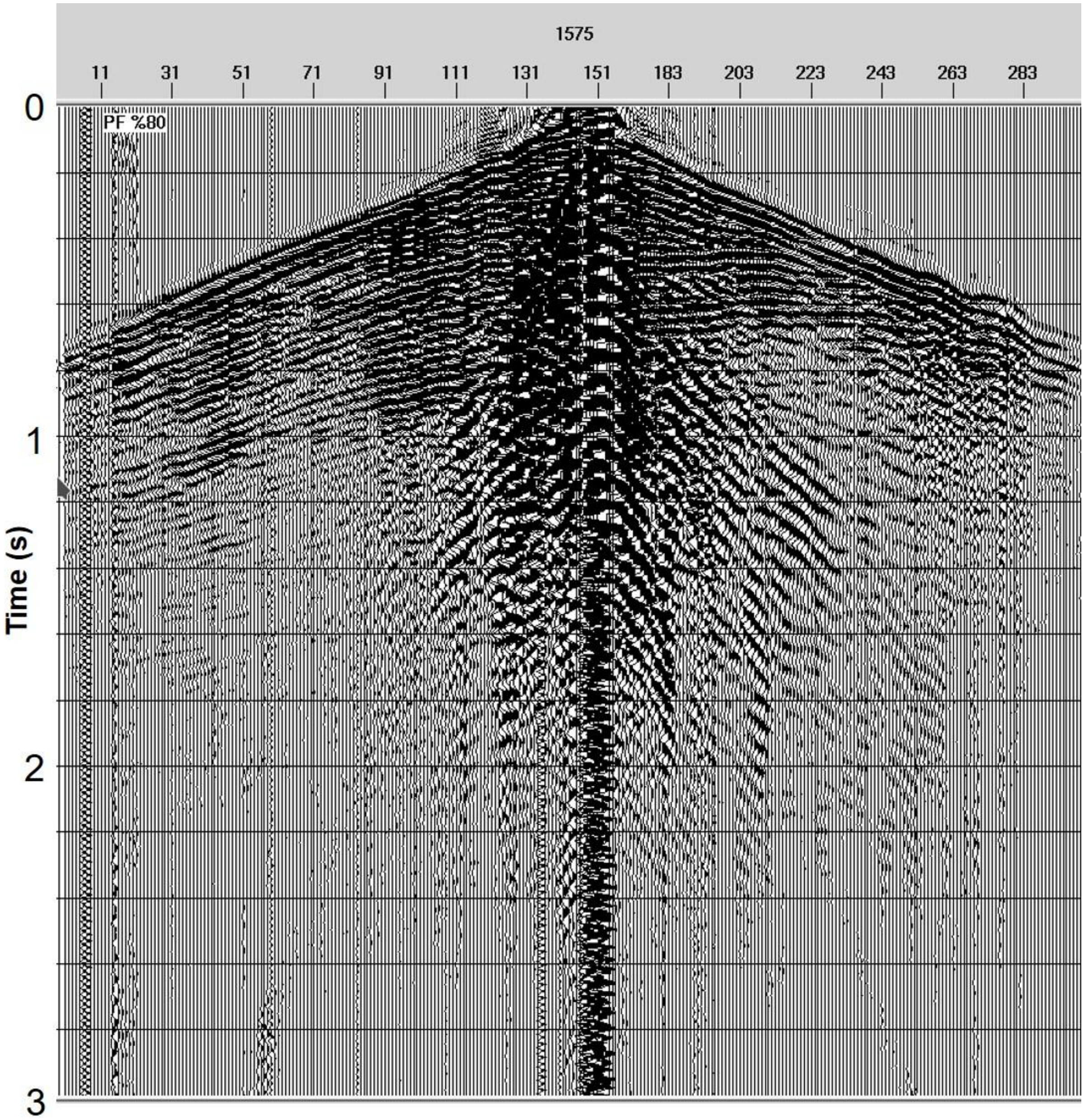

Figure 5d. 3D shot gather with *80%* peak-force (Parameters are 12-64 Hz, 4 sweeps, 12 sec, Non-Linear -3 dB/Oct., 4 vibrators).

Şekil 5d. %80'lik sürüş seviyeli bir sweep ile elde edilmiş 2B atış örneği. (Parametreler 12-64 Hz, 4 sweep, 12 sn, Non-Linear -3 dB/Oct., 4 vibrator).

Amplitude Variation with Number of Vibrator

If in Eq.(8), 1 vibrator is used for sweep, the peak amplitude of autocorrelation will be

$$D = \phi_{ss}(t = 0) = D_o . \quad (13)$$

Eq. (13) gives peak amplitude of autocorrelation at zero time.

If the number of vibrators is d, the peak amplitude of autocorrelation will be

$$D = \phi_{ss}(t = 0) = dD_o .$$

The amplitude of wavelet is proportional to the sweep length and D_o which is the peak amplitude of autocorrelation of one-second sweep length.

The gain obtained, in term of decibel, by length multiplication is

$D = 20\log(dD_o / D_o)$,

$D = 20\log(d)$ dB. (14)

Eq. (14) gives the variation of amplitude of autocorrelation in dB with number of vibrator. Calculated dB value using d vibrators compared with the amplitude of auto-correlated wavelet having one-vibrator is the amount of the amplitude of the auto-correlated wavelet having d vibrators.

Figure 6a shows different autocorrelation wavelets. The amplitude of autocorrelation wavelet is increasing with number of vibrator. In Figure 6b, the increase in amplitude is faster from 1 vibrator to multi vibrators. For example, the increase in amplitude is 6 dB between one and two vibrators but increasing of amplitude from 2 vibrators to 3 vibrators is 4 dB. 2D shot records are shown with 1 vibrator in Figure 6c, and 4 vibrators in Figure 6d. As shown in Figure 6c, amplitude of signal is small and signal to noise ratio is poor. But in Figure 6d, amplitude of signal is bigger and signal to noise ratio is good compare to 1 vibrator.

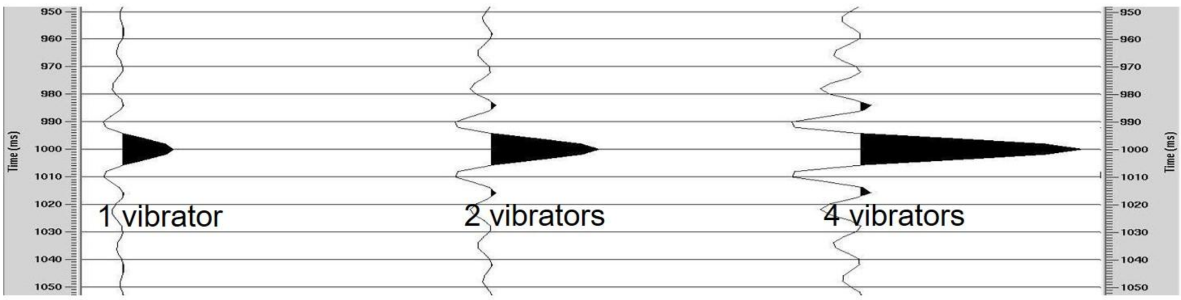

Figure 6a. Autocorrelation wavelets for different number of vibrator.

Şekil 6a. Farklı vibratör sayıları ile elde edilmiş sweep'lerin otokorelasyon dalgacığı.

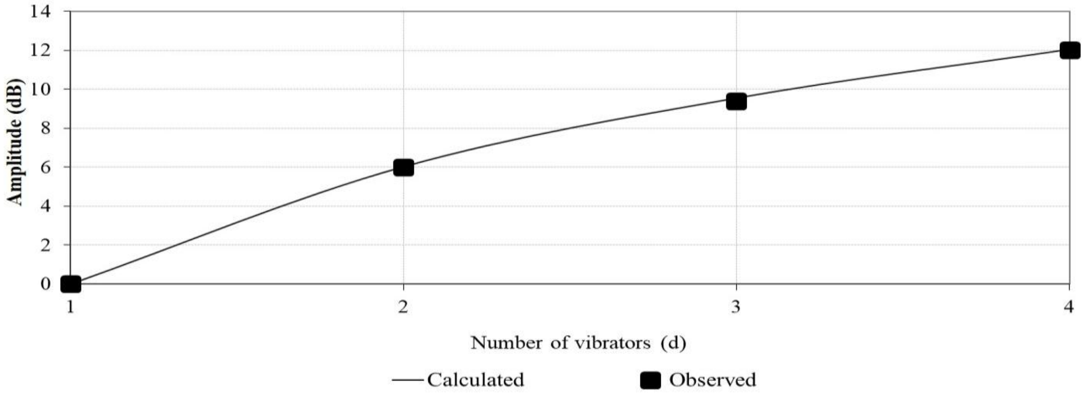

Figure 6b. Variation of peak amplitudes with number of vibrator.

Şekil 6b. Pik genliğin vibratör sayısı ile değişimi.

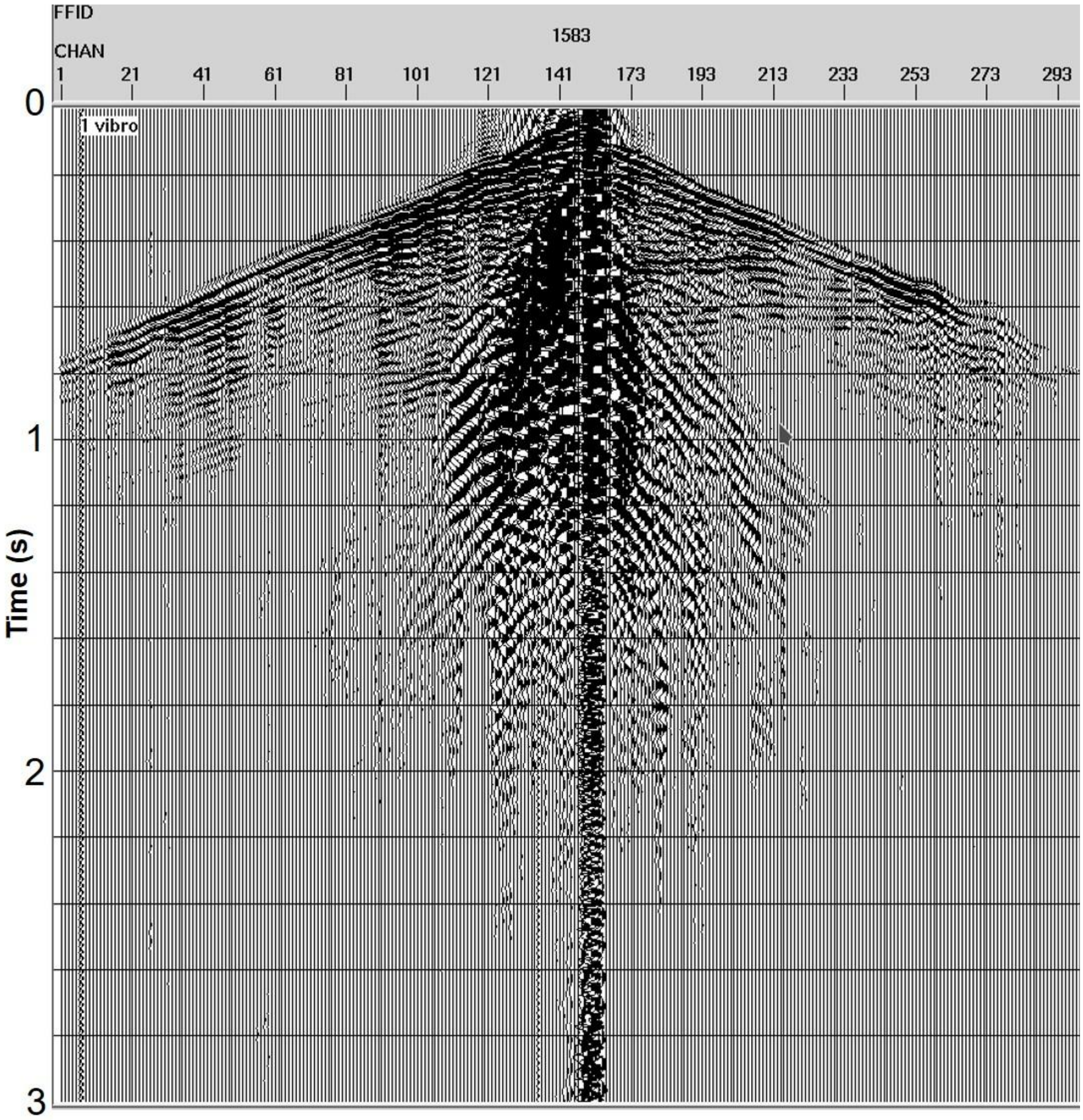

Figure 6c. 2D shot gather with 1 vibrator (Parameters are *12-64 Hz, 4 sweeps,12 sec., Non-Linear -3 dB/Oct., Drive level 80%*).

Şekil 6c. 1 vibratör ile elde edilmiş 2B atış örneği (Parametreler: 12-64 Hz, 4 sweep,12 sn., Non-Linear -3 dB/Oct., Sürüş seviyesi %80).

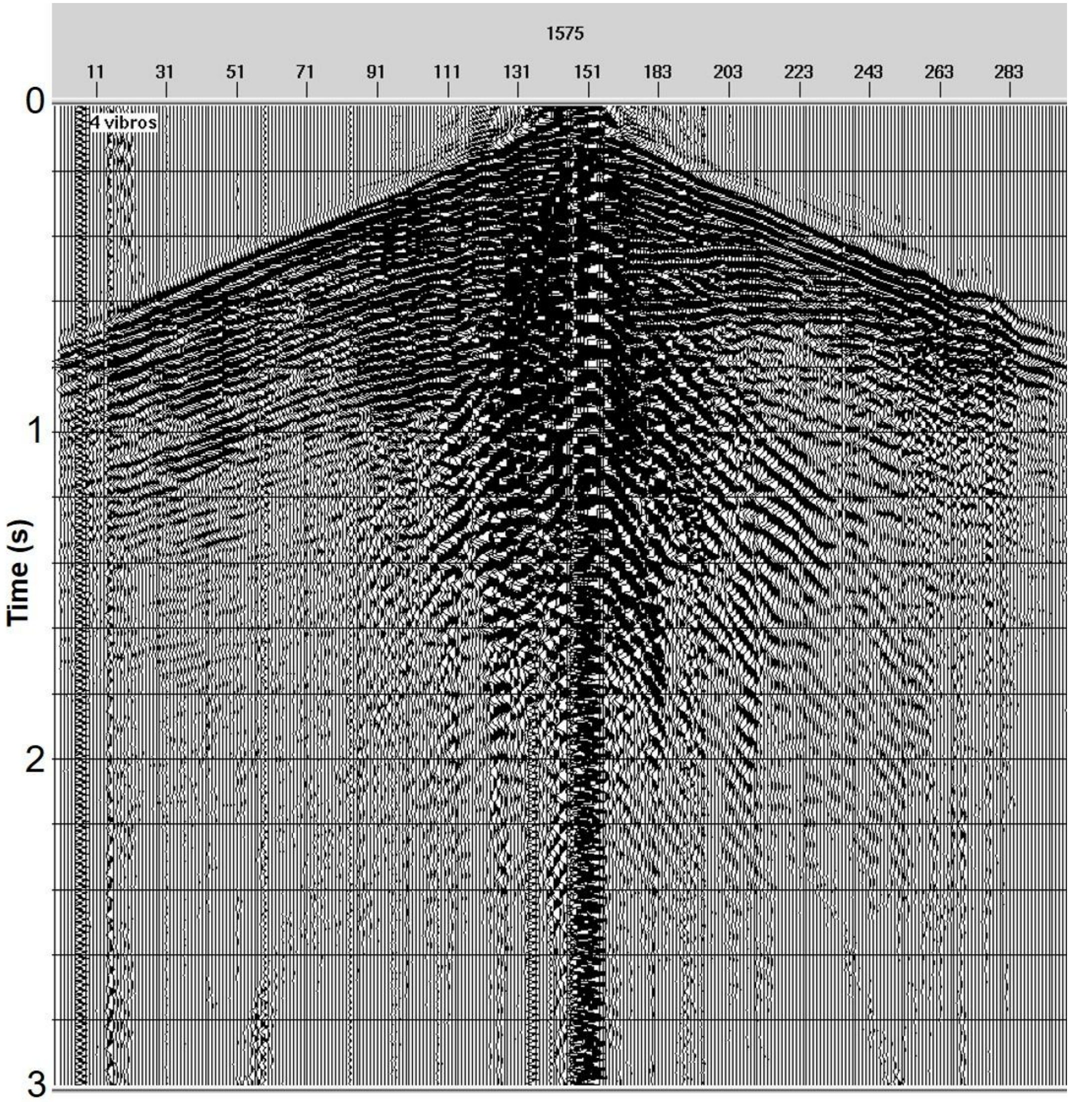

Figure 6d. 2D shot gather with 4 vibrator (Parameters are *12-64 Hz, 4 sweeps, 12 sec., Non-Linear -3 dB/Oct., Drive level 80%*).
Şekil 6d. 4 vibratör ile elde edilmiş 2B atış örneği (Parametreler: 12-64 Hz, 4 sweep, 12 sn., Non-Linear -3 dB/Oct., Sürüş seviyesi %80).

We know that we could improve the quality of seismic data going from 3 to 5 vibrators (Tantawy and Norotte, 1987). Signal/Noise ratio increase and signal amplitude is bigger with the increasing of number of vibrators. We recommend to use shorter sweep signal length if we use multi vibrators. So that daily production will be increased.

Amplitude Variation With Sweep Bandwidth

The amplitude of the wavelet does not vary with sweep bandwidth. Envelope has a maximum at zero lag, comes down to zero, bounces up again, back to zero and up again, and eventually dies away. The time to the first zero, and between subsequent zeros, is the reciprocal of the bandwidth of the sweep.

Cosine wave has a peak at zero lag and a frequency that is the central frequency of the sweep, but its amplitude stays within the envelope.

When we increase the sweep bandwidth, the wavelet is being closed to spike and side-lopes of signal are smaller (Figure 7a). But the amplitude of autocorrelation wavelet is not varying with bandwidth (Figure 7b). Comparison of the narrow band sweep versus wide band sweep signals are shown in Figure 7c and Figure 7d respectfully. Shot record with narrow band 8-48 Hz linear sweep in Figure 7c, resulted in high amplitude of side-lopes and poor signal to noise ratio. Wide band sweep 8-96 Hz, shot record is shown in Figure 7d, amplitude of side-lopes is smaller and signal to noise ratio is good.

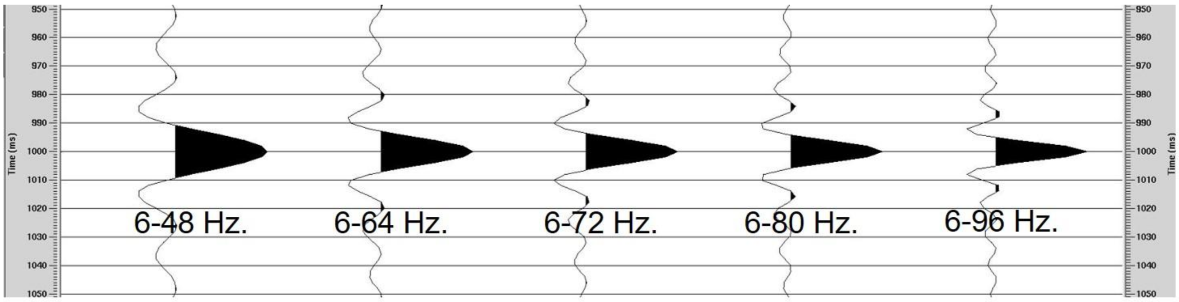

Figure 7a. Autocorrelation wavelets for different sweep bandwidth.

Şekil 7a. Farklı sweep band genişliği ile elde edilmiş sweep'lerin otokorelasyon dalgacığı.

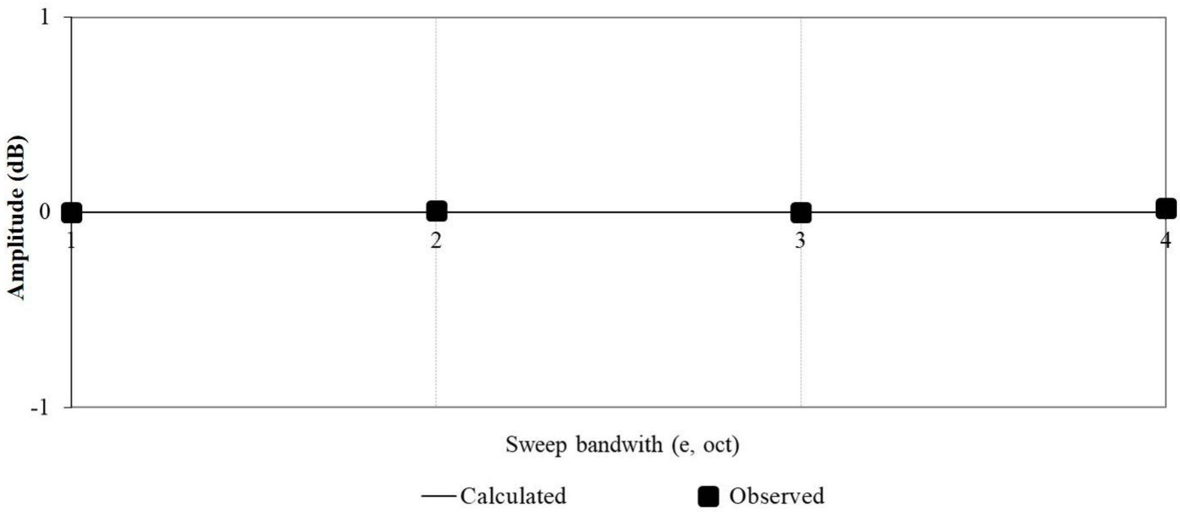

Figure 7b. Variation of peak amplitudes with sweep bandwidth.

Şekil 7b. Pik genliğin sweep band genişliği ile değişimi.

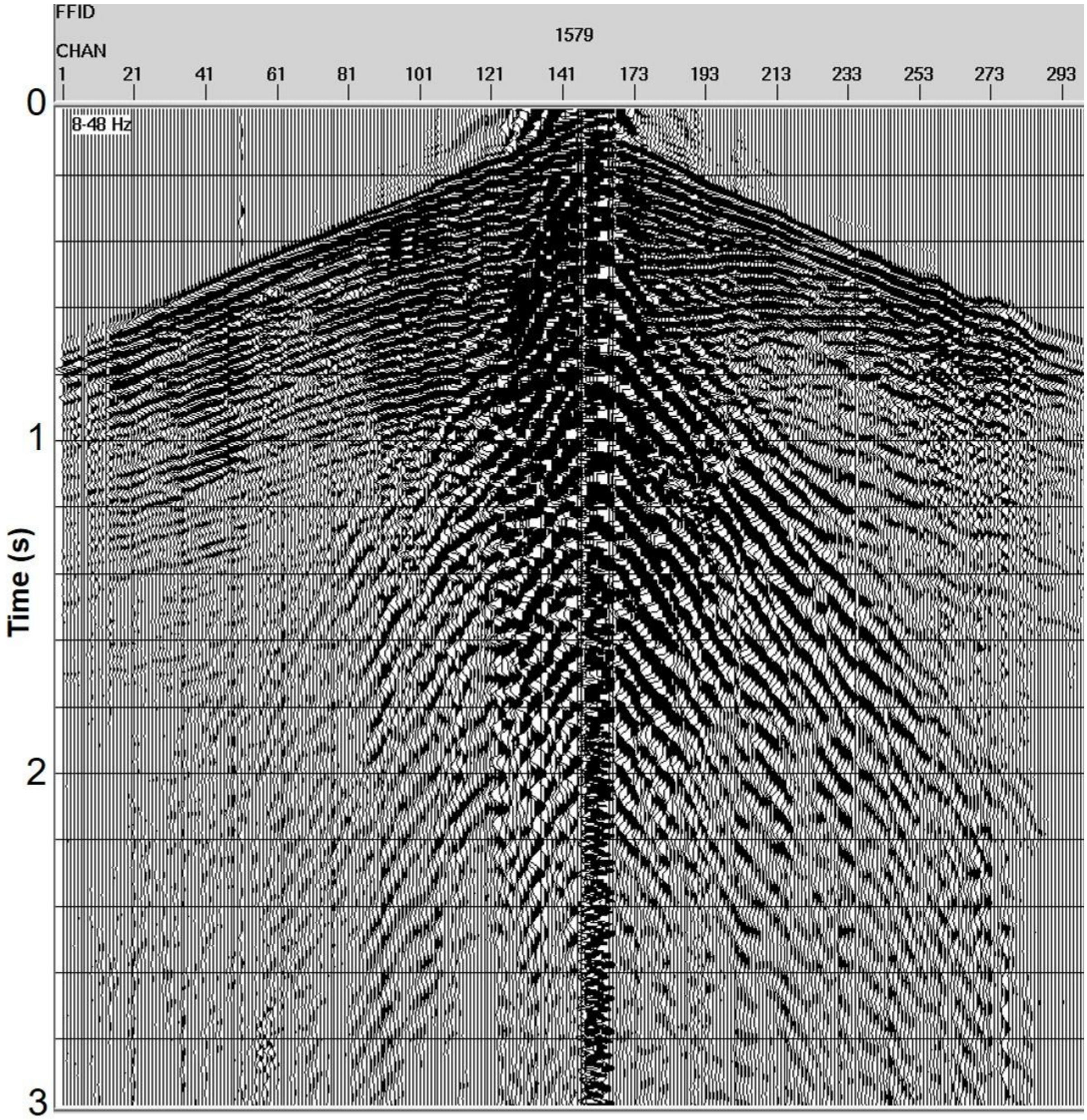

Figure 7c. 2D shot gather with narrow bandwidth (Parameters are *8-48 Hz, 4 sweeps, 12 sec., Non-Linear -3 dB/Oct., Drive level 80%, 4 vibrators*).

Şekil 7c. Dar frekans band aralığı ile elde edilmiş 2B atış örneği (Parametreler 8-48 Hz, 4 sweep, 12 sn., Non-Linear -3 dB/Oct., Sürüş seviyesi %80, 4 vibrator).

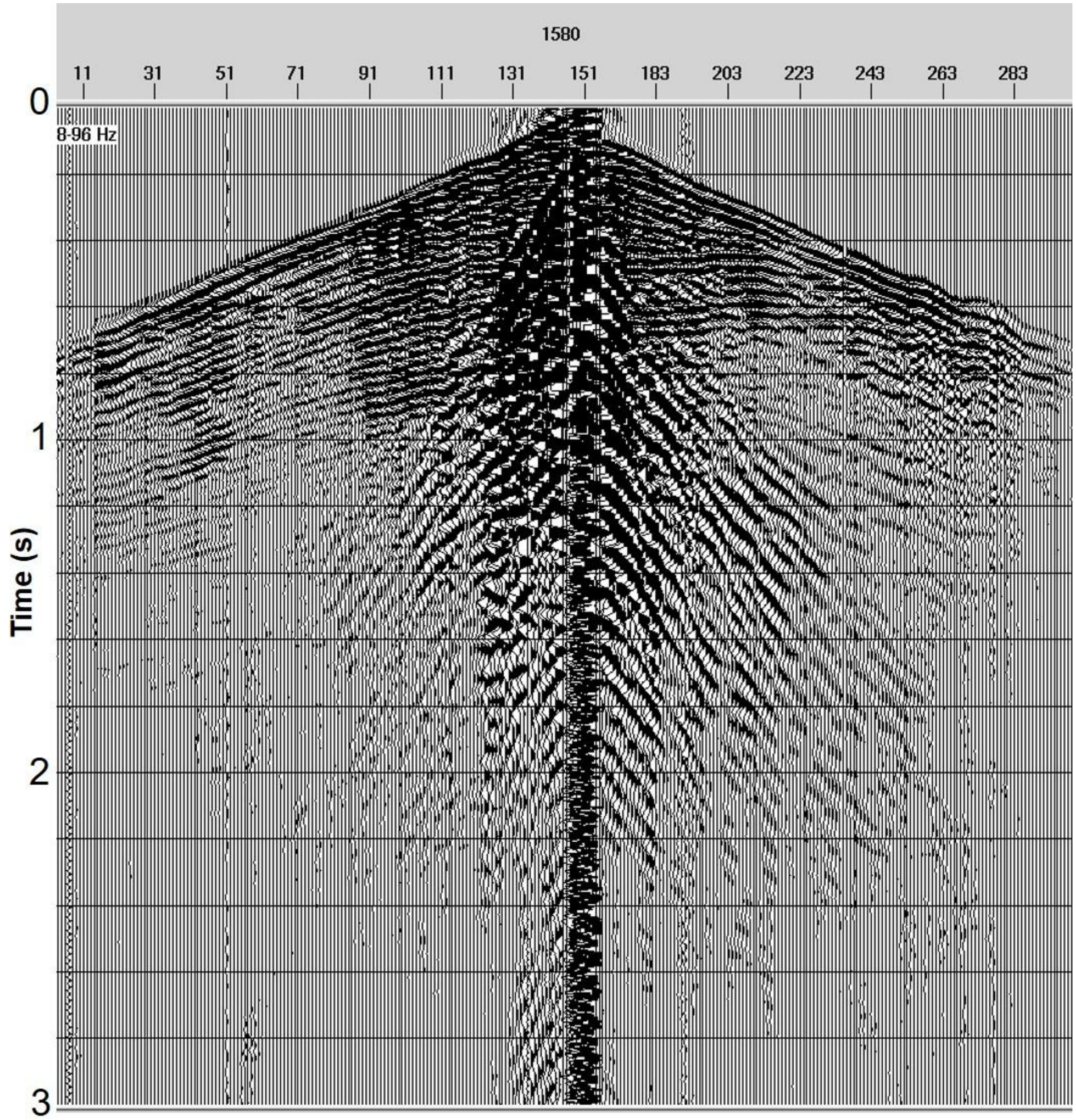

Figure 7d. 2D shot gather with wide bandwidth (Parameters are *8-96 Hz, 4 sweeps, 12 sec., Non-Linear -3 dB/Oct., Drive level 80%, 4 vibrators*).

Şekil 7d. Geniş frekans band aralığı ile elde edilmiş 2B atış örneği (Parametreler 8-96 Hz, 4 sweep, 12 sn., Non-Linear -3 dB/Oct., Sürüş seviyesi %80, 4 vibrator).

Combining All The Formulas

If we use, number of sweep is a, sweep length is b sec, peak-force ratio of the vibrator is c and number of vibrators is d related peak amplitude of autocorrelation (G) is

$G = a^2 bcdA_o B_o C_o D_o$ (for correlation after stack), (15)

$G = abcdA_oB_oC_oD_o$ (for correlation before stack). (16)

For unit values of the parameters namely for $a=1$, $b=1$sec., $c=1$(peak force 100%) , $d=1$ vibrator Eq. (15) and Eq. (16) may be expressed as

$G = G_o = A_oB_oC_oD_o$. (17)

where G_o is peak amplitude of autocorrelation (Eq. 17) for unit values of the parameters.

Using Eq. (15) and Eq. (16) general case may be put in the following form

$G = a^2bcdG_o$ (for correlation after stack), (18)

$G = abcdG_o$ (for correlation before stack). (19)

What is found for the autocorrelation of sweep is valid also for the correlated data taking into account Eq. (A.6). Eq. (18) and Eq. (19) are found by Sakallioglu et al. (2012).

The effect of the different sweep signals and vibrator peak force ratio is shown in Figure 8a and Figure 8b. These are not the same line but very closely located and parallel to each other. Test line data processed with same processing sequences and parameters. For line-A, Heavy Vibrators (HV) were used, but for line-B, Light Vibrators (LV) were used (Table 1). Test lines results are shown in Figure 8a HV, 4 sweeps per VP and Figure 8b LV with 6 sweeps per VP.

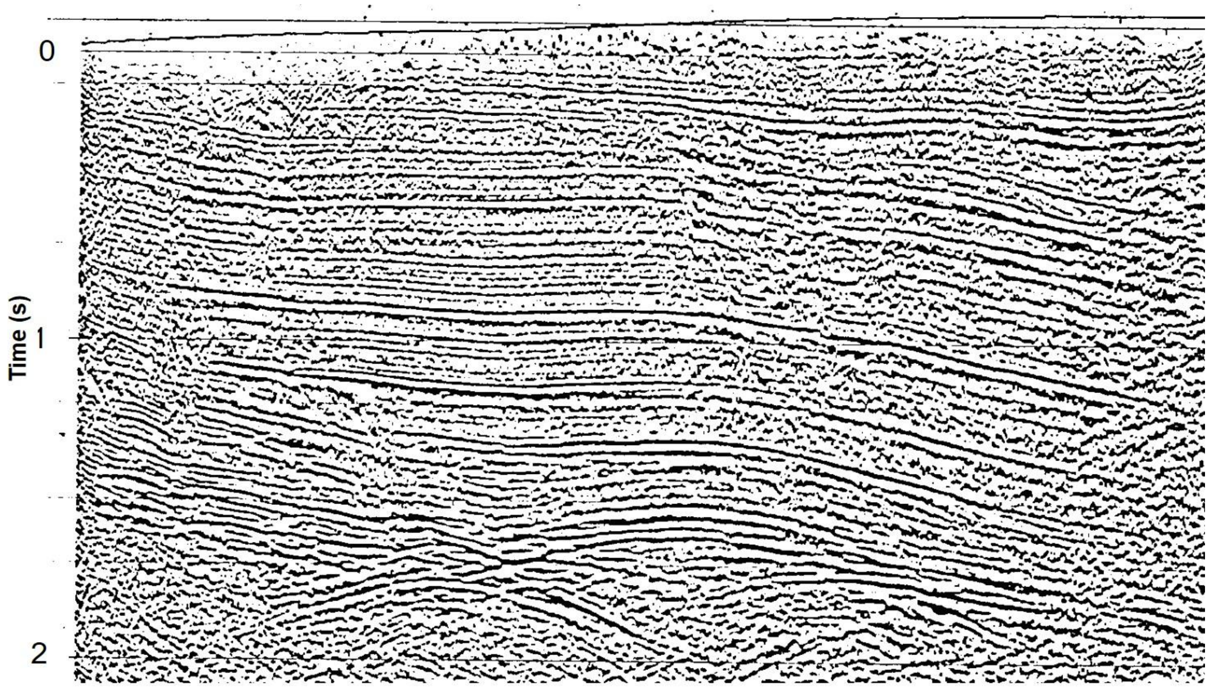

Figure 8a. Example of seismic section with 4 sweeps line-A (Parameters are 10-72 Hz, 8 sec., Linear, Drive level c= 80%, 4 vibrators).

Şekil 8a. 4 sweep'li Line-A sismik kesit örneği (Parametreler 10-72 Hz, 8 sn., Linear, Sürüş seviyesi c= %80, 4 vibrator).

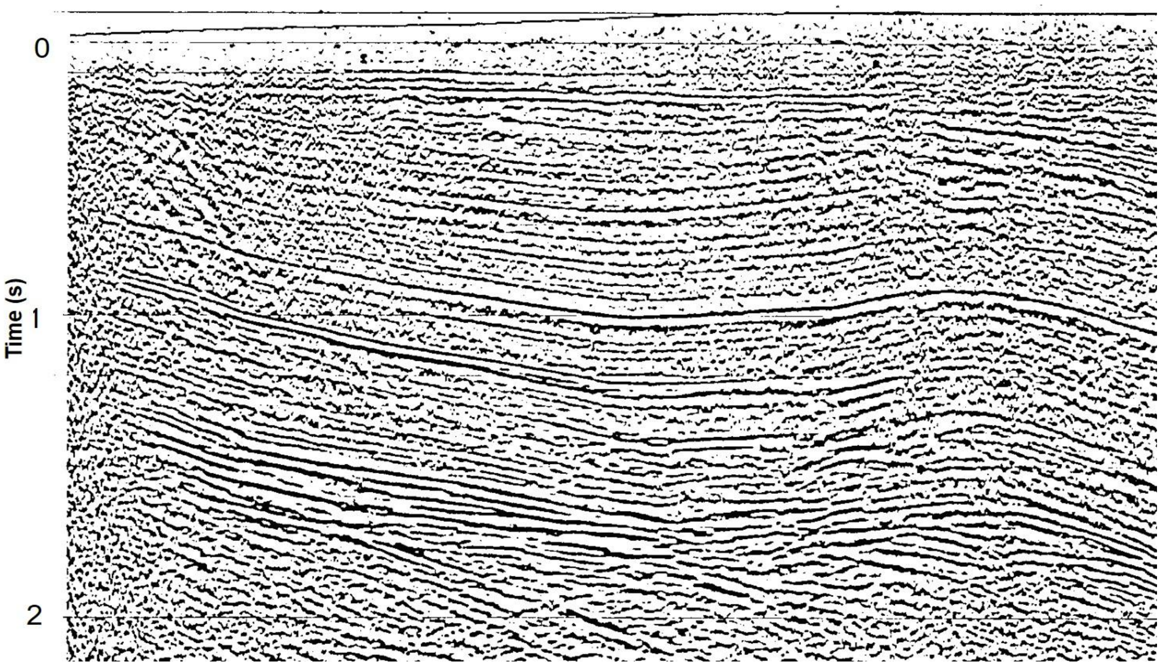

Figure 8b. Example of seismic section with 6 sweeps line-B (Parameters are 10-72 Hz, 8 sec., Linear, Drive level c=37%, 4 vibrators).

Şekil 8b. 6 sweep'li Line-B sismik kesit örneği (Parametreler 10-72 Hz, 8 sn., Linear, Sürüş seviyesi c=%37, 4 vibrator).

A comparative table (Table 1) is presented with the definitions of LV and HV. One must keep in mind that maximum utilizable peak force of a vibrator is about 80% of its theoretical force. We see from the table that maximum utilizable the peak force of LV is equal to 37% of theoretical peak force value of HV. Same table shows that in order to get the same quality by using HV and less number of sweeps recording production increases %30 as compared to the LV.

Table 1. Comparison of light and heavy vibrator.

Çizelge 1. Hafif ve ağır vibratörün karşılaştırması.

	Light Vibrator (LV)	Heavy Vibrator (HV)
Number of sweep (a)	6	4
Shot interval	50 m	50 m
Receiver interval	50 m	50 m
Sweep length (b)	8 sec	8 sec
Peak force	32.000 pounds	62.000 pounds
Drive level or Peak force (c)	80 % (%37 of HV)	80 %
Number of vibrator (d)	4	4
Sweep time	6swp*(8sec+5sec)=78 sec	4swp*(8sec+5sec)=52 sec
Moving time	35 sec	35 sec
Total times/shot	78+35=113 sec	52+35=87sec
Gain of one shot	0	30%
Amplitude	106.56 units	108.80 units
Amplitude	40.55 dB	40.73 dB

LV: Light vibrator, weight: 19 tons   HV: Heavy vibrator, weight: 30 tons

We have results of daily recording productions of LV (Figure 9a) with 37% peak-force and 6 sweeps, Average records were 178 VP’s/day. When we increase 80% peak-force and application of 4 sweeps (Figure 9b) average daily recording productions were 230 VP’s/day. Therefore, daily production increased with HV and less number of sweeps per VP. So that the cost of seismic data acquisition will be decreased.

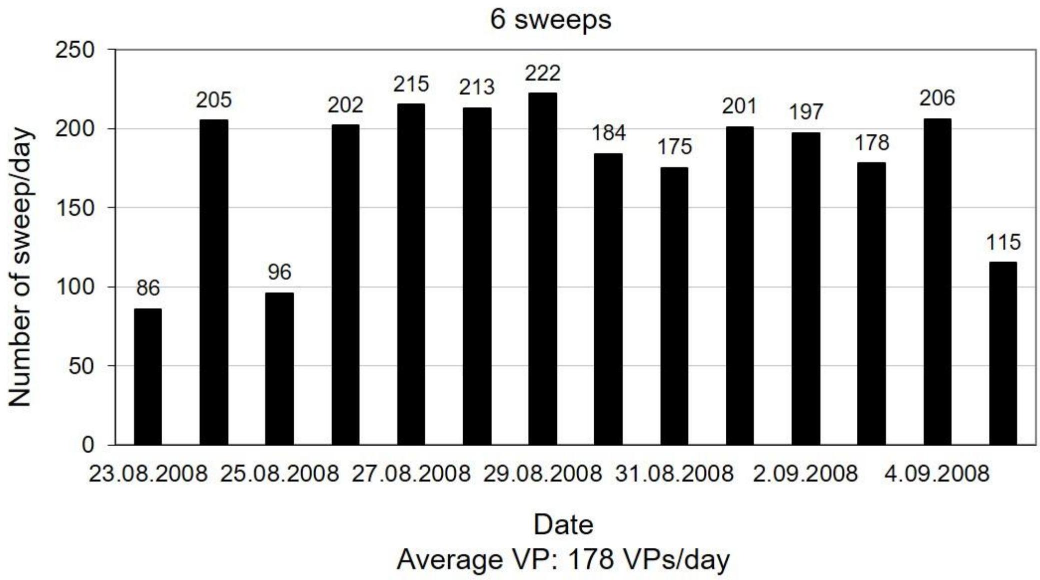

Figure 9a. Daily Recording Production of Light Vibrators (LV) with 6 sweeps and Peak Force 37%.

Şekil 9a. 6 sweep ve %37 sürüş seviyeli hafif vibratör ile yapılan günlük atış sayıları.

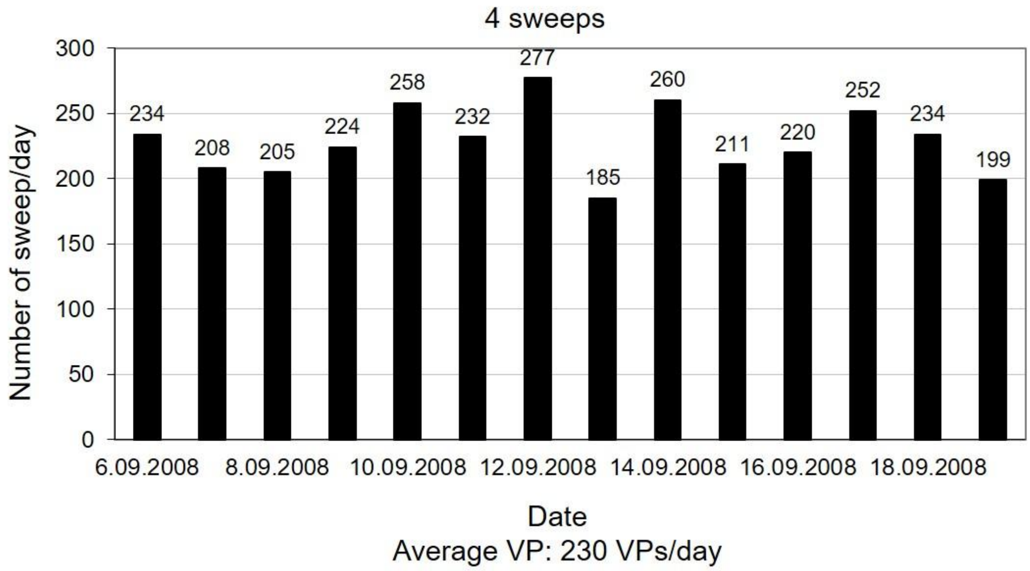

Figure 9b. Daily Recording Production of Heavy Vibrators (HV) with 4 sweeps and Peak Force 80%.

Şekil 9b. 4 sweep ve %80 sürüş seviyeli hafif vibratör ile yapılan günlük atış sayıları.

As shown in Eq. (28a), the wavelet amplitude can be preserved by changing of sweep signal parameters. One parameter in the equation can be reduced and the other parameters can be increased. Thus, the quality is maintained at a certain level.

By changing vibrosesis sweep signal parameters, number of vibrators and peak force, it is possible to carry out seismic survey in the urban areas, around the villages, cities and along the roads, etc…

In Eq. (18), a=4 (number of sweep per VP), b=12 sec (sweep length), c=0.8 (%80, Peak force) and d=4 (Number of vibrator) are given,

$G=4^2*12*0.8*4*G_o$,

$G=614.4*G_o$. (20)

Eq. (20) gives the amplitude of autocorrelation according to above parameters. By the same equation if b=12 sec, c=0.4 (%40) and d=4 are taken, the “a” (as the sweep number) can be computed for same G:

$G=614.4*G_o=a^2*12*0.4*4*G_o$,

$a^2=32$,

$a=5{,}7$ sweeps. (21)

Eq. (21) gives the required number of sweeps (a) for the same G value in Eq. (20). Namely, if peak force is reduced from %80 to %40, number of sweep should be minimum 5.7 sweeps for same peak amplitude of autocorrelation (G). In practice, selected number of sweep is minimum 6 sweeps for same G.

2D shot records are shown 6 sweeps with %40 of peak force in Figure 10a, 4 sweeps with %80 of peak force in Figure 10b. Thus, they resulted in almost same shot records, because peak amplitude of autocorrelation (G) is almost the same. Using this method, vibrators can be used in urban areas, on asphalt roads, in village etc. (Figure 10c).

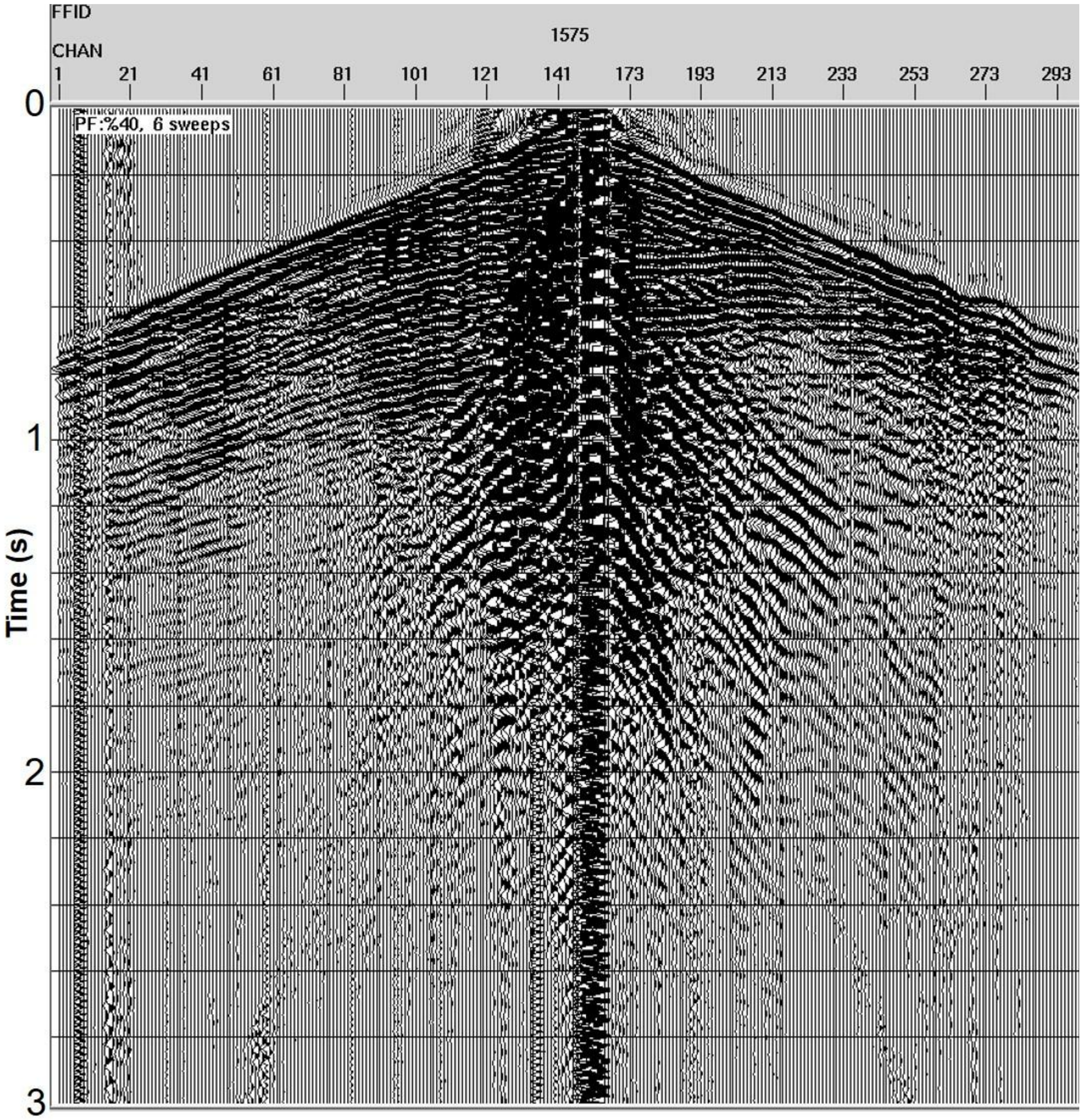

Figure 10a. 2D shot gather with Drive level 40% (Low force) and 6 sweeps (Parameters are 12-64 *Hz, 12 sec., Non-Linear -3 dB/Oct., 4 vibrators*).

Şekil 10a. 6 sweep ve %40 sürüş seviyeli 2B atış örneği (Parametreler 12-64 Hz, 12 sn., Non-Linear -3 dB/Oct., 4 vibratör)

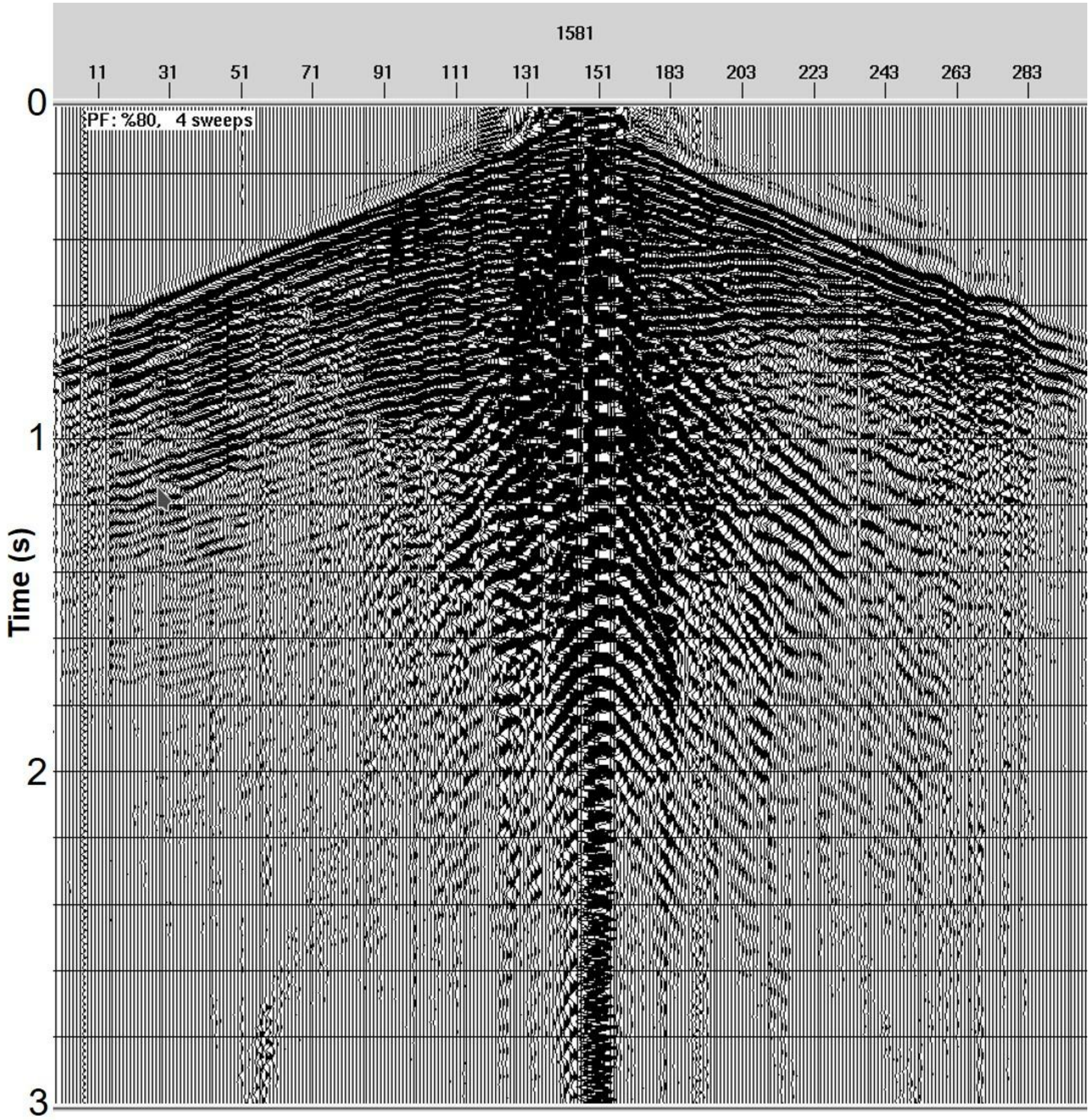

Figure 10b. 2D shot gather with Drive level 80% (High force) and 4 sweeps (Parameters are 12-64 *Hz, 12 sec., Non-Linear -3 dB/Oct., 4 vibrators*).

Şekil 10b. 4 sweep ve %80 sürüş seviyeli 2B atış örneği (Parametreler 12-64 Hz, 12 sn., Non-Linear -3 dB/Oct., 4 vibratör)

Figure 10c. A view of vibrators on asphalt road and near to factory.

Şekil 10c. Fabrikaya yakın ve asfalt yol üzerindeki vibratörlerin görünüşü.

CONCLUSIONS

1. The signal amplitude is proportional to the square of the number of sweep per VP as show by the Eq. (5),
2. The signal amplitude is proportional to the sweep length itself, longer sweep signal length increase the signal amplitude Eq. (10),
3. The signal amplitude is proportional to % of Peak-force itself,
4. S/N ratio of data is proportional to the square root of: number of sweep, sweep signal length and peak force multiplication.
5. For deep targets; linear sweep type, more number of sweep and longer sweep signals are recommended,
6. For shallow targets; non-linear or logarithmic sweep signal type, less number of sweep signal and shorter sweeps are recommended,
7. For deep targets; low frequency start-up, more number of vibrators and longer sweep signals are recommended,
8. For shallow targets; broad band sweep signal, less number of vibrators and short sweep signals are recommended,
9. By using heavy vibrators and high Peak Forces with less number of sweeps per VP, less number of vibrators and shorter sweep signal length provide almost the same quality data by using light vibrators and less Peak Force with more number of sweep per VP, more number of vibrators and longer sweep signal length.
10. Heavy vibrators are more productive then light vibrators,

11. It is possible to work with vibrators in the urban areas, asphaltic roads or in the village by the application of optimum vibroseis sweep signal parameters.

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APPENDIX:

Autocorrelation and cross-correlation

If we introduce the input signal $s(t)$ into the earth, the recorded data $p(t)$ is the result of the convolution of the signal $s(t)$ with $Q(t)$, the impulse response of the subsurface

$$p(t) = \int_{-\infty}^{+\infty} Q(\tau)s(t-\tau)d\tau + n(t)\,. \qquad \text{(A-1)}$$

$$p(t) = Q(t) * s(t) + n(t)\,.$$

where * and $n(t)$ represent the convolution notation and noise, respectively.

Autocorrelation of the signal $s(t)$ is expressed as

$$\phi_{ss}(t) = \int_{-\infty}^{+\infty} s(\tau)s(t+\tau)d\tau\,. \qquad \text{(A-2)}$$

with

$$\phi_{ss}(t=0) = \int_{-\infty}^{+\infty} [s(\tau)]^2 d\tau\,.$$

Corresponding to zero shift value of the autocorrelation. We can put Eq. (A-2) using convolution notation in the form

$$\phi(t) = s(t) * s(-t)\,. \qquad \text{(A-3)}$$

to the same way, the cross-correlation between $p(t)$ and $s(t)$ can be written as

$$\phi_{ps}(t) = p(t) * s(-t)\,. \qquad \text{(A-4)}$$

combining Eq. (A-1), Eq. (A-3) and Eq.(A-4) we obtain

$$\phi_{ps}(t) = Q(t) * s(t) * s(-t) + n(t) * s(-t)\,. \qquad \text{(A-5)}$$

neglecting the noise term, final data becomes

$$\phi_{ps}(t) = Q(t) * \phi_{ss}(t)\,. \qquad \text{(A-6)}$$

This last equation says that $\phi_{ps}(t)$ represents the convoluted form of the reflection coefficient distribution of the subsurface. That is what we are trying to obtain by seismic recording.