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MEASUREMENT OF THE SEISMIC WAVES PROPAGATION VELOCITY IN THE REAL MEDIUM

UDC: 556.556+632.126

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Abstract. *In this work, an effective technique for the measurement of seismic wave propagation velocity in the real geological medium is presented. The propagation velocities of seismic waves vary in different types of geological media from 100 m/s to 6800 m/s. Due to this, it is necessary to evaluate the propagation of the seismic wave front between the different points in the real media. The signal time delay is determined by locating the peak in the cross-correlation function, obtained by the correlation of the signals from these sensors. The efficiency of this method is illustrated with experimental results.*

1. INTRODUCTION

Measurement of the seismic wave propagation velocity in the given geological area is of the fundamental importance for determination of the source location. Due to this, it is necessary to evaluate the propagation of the seismic wave front between the different points in the ground. During the seismic waves propagation, the front of the waves occupies distinct positions in the successive time instants. Seismic wave [3], generated under the action of the short pulse, is a complex wave that consists of the following components (Fig. 1):

- Longitudinal - compressive *P*-wave;
- Transverse *S*-wave;
- Rayleigh - Surface *R*-wave.

Longitudinal *P*-waves and transverse S-waves are known as the body waves. Body waves are propagating through the medium by means of the hemispherical wavefront. The type of the component being considered depends on the source of vibrations. Rayleigh wave, which is propagated radially and has the cylinder-like wavefront, appears simultaneously with the body waves. Displacement of the ground in the vertical direction

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at the certain distance from the excitation point is illustrated in Figure 2.

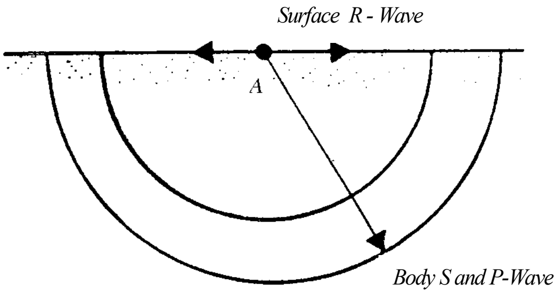


Fig. 1. Propagation of the surface and body waves (A is the point of the excitation).

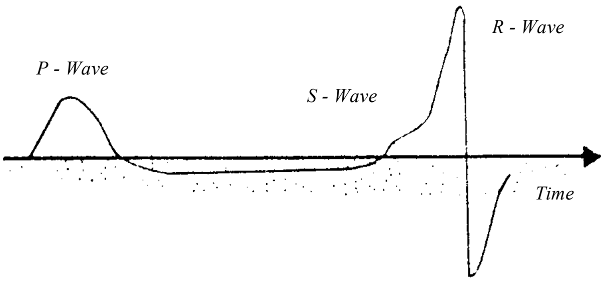


Fig. 2. Vertical displacement of the medium particles on the surface caused by the impulse excitation.

2. PRELIMINARIES

During the propagation through an elastic medium, components of the complex seismic wave have different velocities [3]. Since the P-waves are faster than the other types of seismic waves, they can at first be detected by the sensors. P-waves are followed by the S-waves and Rayleigh - waves, respectively. As illustrated in Fig. 2, the vertical distance of the ground caused by the Rayleigh waves is greater than the distance caused by the remaining P and S-waves. The amplitude of the waves is considerably reduced with the increase of the distance from the source. The energy of the body waves is distributed through the medium according to the following expression:

$$E \approx \frac{1}{r^2}, \tag{1}$$

where E is the energy of surface density, and r is the radius of the sphere. The amplitude of the seismic wave is proportional to the square root of the energy surface density:

$$Amplitude \approx \sqrt{E}\ , \tag{2}$$

$$Amplitude \approx \frac{1}{r}, \tag{3}$$

Since the body waves are propagated through the semi-sphere only, the amplitude of the body waves is proportional to:

$$Amplitude \approx \frac{1}{r^2}, \tag{4}$$

The amplitude of the Rayleigh waves is proportional to:

$$Amplitude \approx \frac{1}{\sqrt{r}}, \tag{5}$$

where r is the radius of the cylinder. The attenuation of the Rayleigh waves is significantly less than that of the body waves. Rayleigh wave appears in the case of two adjacent elastic mediums with different elastic properties. This wave is similar to the wave generated by a stone thrown into the water. The velocity of the surface Rayleigh waves [1] is given by:

$$V_R = 0.9V_s, \tag{6}$$

where V_s is the velocity of transverse waves in the same medium. Longitudinal waves propagate more slowly then direct transverse *S*-waves along the same trace, and even more slowly than direct longitudinal *P*-waves, so the following relation holds:

$$V_P > V_S > V_R, \tag{7}$$

By the pulse excitation in the point $A(x,y)$, Fig. 1, a surface seismic wave, moving at a constant velocity in the form of concentric circles, is generated.

Geophones placed at different distances from the source point induce the presence of the wavefront [4-8]. The medium vibrations take place in all three dimensions, but only the vibration of the medium particles in vertical direction is used for measurement of the seismic wave velocity. By detecting the vertical displacement of the medium particles in time, we obtain the vibration curves.

Oscillations propagate through elastic geological mediums with different properties, so the vibration curves are not always identical. The number and the relative ratio of the peaks of vibration curves remain constant. The property of seismic wave propagation to retain the similarity between vibration curves of two distant points enables determination of the seismic wave delay time. Comparing the vibration curves for the two medium points chosen in advance, the propagation of the given seismic wave can be determined.

The knowledge of exact numerical value of the seismic wave propagation velocity is a necessary parameter for the determination of unknown location of the seismic wave source [4-8]. In all presented methods for the location of the unknown source of seismic waves, the velocity of seismic wave propagation is the necessary parameter. Necessary parameters for realisation of the algorithm for the determination of unknown location of the seismic wave source are knowledge of the seismic wave velocity and the distance beetven the sensors. The distance L can be obtained from equation (8):

$$L = v\,t, \tag{8}$$

where L is the distance that seismic wave covers from the source location to the actual sensor, V is the seismic wave propagation velocity, and t is the time of seismic wave propagation from the source of excitation to the sensor. The method developed for the measurement of the seismic wave propagation velocity at the actual terrain consists of the following:

- On the terrain for which we want to calculate the seismic wave propagation velocity, the electromagnetic seismic sensors - gephones are placed in the linear constellation at known distances.
- In the direction of the placed sensors, a pulse excitation is applied to the earth surface. It is desirable to eliminate other excitations in the local environment of the actual terrain in order to prevent other unwanted wavefronts to reach the sensors.

3. EXPERIMENTAL DETAILS

The geometrical constellation of the sensors shown in Fig. 3 is used for the measurement of the seismic wave propagation velocity in the same direction.

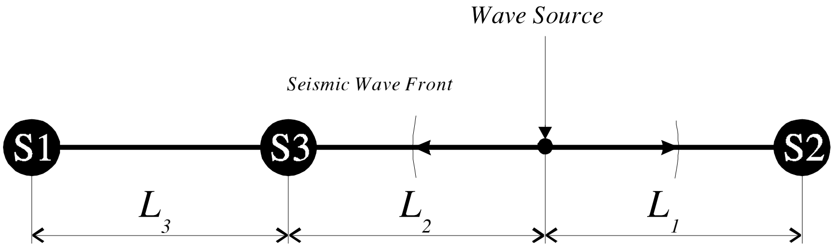


Fig. 3. The geometrical constellation of the sensors and the seismic source during the measurement of the seismic wavefront velocity in the sensor direction

In the experiment, the distances were:

$$L_1 = L_2 = L_3 = 20m \tag{9}$$

The conditions were set by the relation (9) so that in the case of the homogenous medium the signals detected by the sensors S2 and S3 would be identical. These signals serve for the verification of the correctness of the experiment, i.e. for the confirmation of the homogeneity of the medium along the actual direction. The method of cross-correlation is used for the calculation of the time delay of the signals from the sensors S2 and S3 [2, 4].

In Fig. 4, real seismic signals detected by all three sensors for the same excitation are shown. A considerable similarity of the signals from the sensors S2 and S3 is obvious. The calculated seismic signal time delay in these sensors is 1 ms, and an analog-digital conversion is performed with the sampling frequency of 1 kHz.

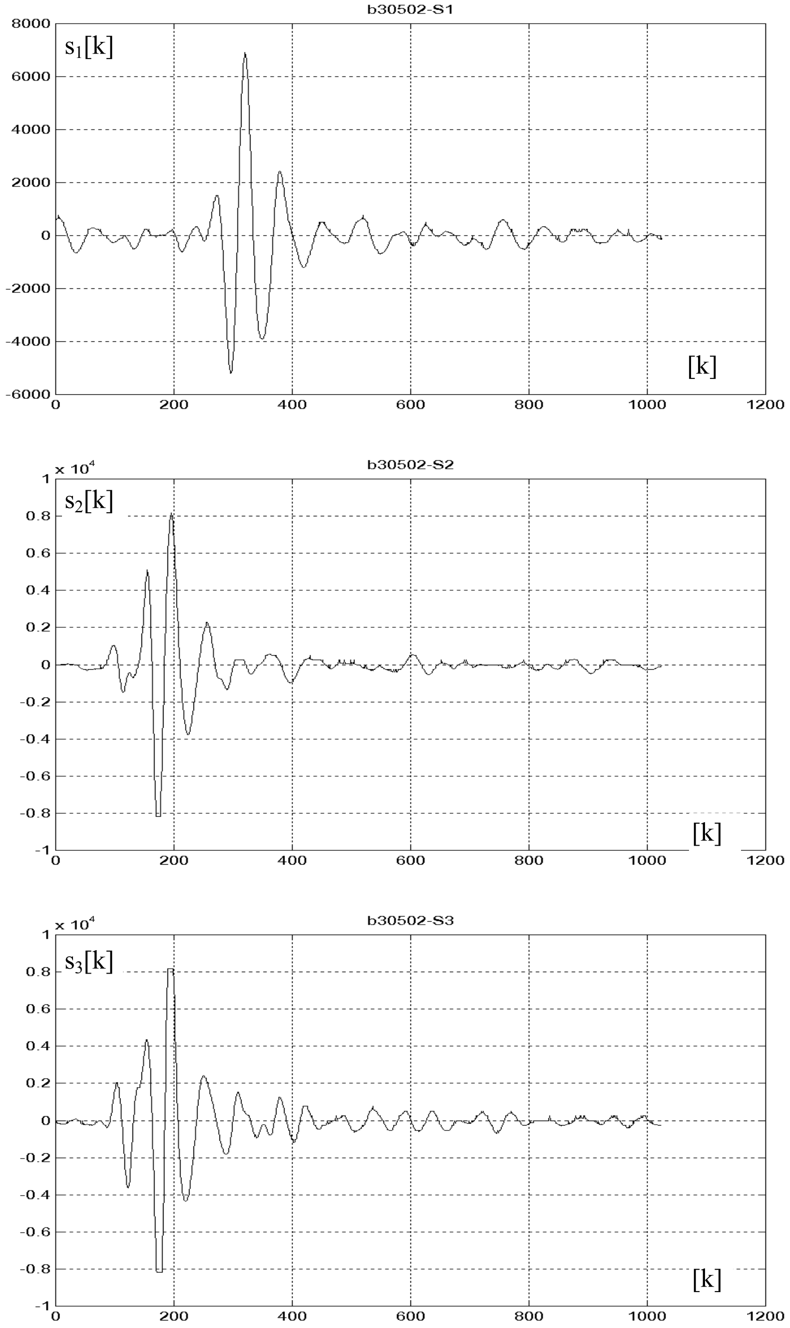


Fig. 4. Real seismic signal detected by three sensors for the same impulse excitation.

The difference between the seismic wave propagation times in sensors S2 and S3 for the correctly performed experiment should be zero, i.e. for homogenous geological medium it is expected that seismic wavefront propagation times should be equal. Due to the medium, which is not identical from place to place, satisfactory results are obtained if the difference in the propagation times is 1-3 sampling periods. For the sampling frequency of 1 kHz, this error is 1-3 ms. The obtained results are a practical verification of whether the analyzed terrain can be approximated as an elastic medium, or whether this approximation is not valid.

By observing the waveform of the signals detected by the sensors S2 and S3, and the relation between the signal peaks, the homogeneity of the examined direction on the considered terrain can be verified. If the signals are identical or similar in their waveforms, the actual medium is homogenous, otherwise the examined medium is not homogenous and it is necessary to determine the seismic wave velocity in all directions. The signals detected by the sensors S2 and S3 can not be used for the calculation of the seismic wave velocity, since the difference between the propagation times in these sensors is zero.

To calculate the seismic wave velocity, the signals detected by the sensors S1 and S3 which are not at the same distance, have to be correlated. The adopted distance between the sensors is 20 m, and source of excitation is 20 m away from the nearest sensor S3. By correlating the signals in the sensors S1 and S3, the seismic wave propagation time from the location of the sensor S3 to the sensor S1 is obtained. The location of the excitation can be arbitrarily far from the sensor, but has to be in the direction defined by the sensors S1 and S3. The impulse excitation must have intensity high enough to cause excitation of all the sensors, including the farthest one from the seismic excitation source. By visually comparing the waveforms of the detected signals, it can be observed that the peak of the signal from the sensor S1 is delayed compared to the signal peaks from the other sensors. By calculating the cross-correlation function between the signals S1 and S3, and then by finding the peak of the cross-correlation function, the obtained time delay of the seismic signal from the sensor S1 compared to the sensors S2 and S3, equals 124 ms. Algorithm for determination velocity of seismic waves [4] for sensors constellation shown in Fig. 4 is illustrated on Fig. 5.

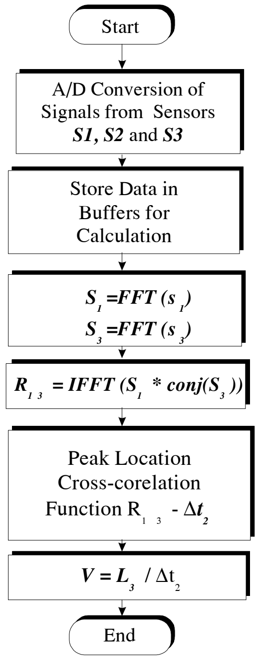


Fig. 5. Algorithm for determination seismic waves propagation velocity in the real seismic medium.

4. RESULTS AND DISCUSSION

The detection of the shown real seismic signals was performed on the hunting ground "Karadjordjevo" in June 1996. A few hundred of measurements were performed, and some of the results are presented in Table 1.

Table 1. Calculated delay times: Δt_1 between signal in sensors S1 and S2; Δt_2 between signal in sensors S1 and S3; Δt_3 between signal in sensors S3 and S2

Signal number	delay Δt_1 [ms]	delayΔt_2 [ms]	delay Δt_3 [ms]	Velocity [m/s]
1	122	126	4	158.73
2	123	126	3	162.60
3	124	126	2	161.29
4	125	126	1	160.00
5	124	125	1	160.00
6	123	126	3	158.73
7	124	125	2	160.00
8	123	124	1	161.29
9	125	126	1	158.73
10	124	125	1	160.00
average	123.7	125.5	1.9	159.36

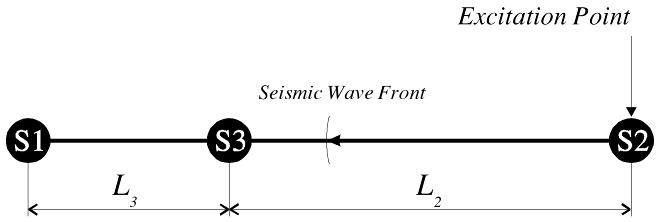
The first column shows the names of the files under which the detected signals are memorized on a hard disk. The second column shows the calculated results of the signal delay in the sensors S1 and S2, the third column shows the obtained results for the signal delay time in the sensor S1 and S3. The fourth column represents the signal delay in the sensor S2 compared to the sensor S3, and it represents the delay which is used for the control of the obtained results. This delay should equal zero in an ideal case, as the sensors S2 and S3 are placed at the same distance from the seismic wave excitation source where the signal delays should be equal.

At the end of the table, the calculated seismic wave propagation velocity is given. The velocity in the case shown in Fig. 4 is calculated by the formula:

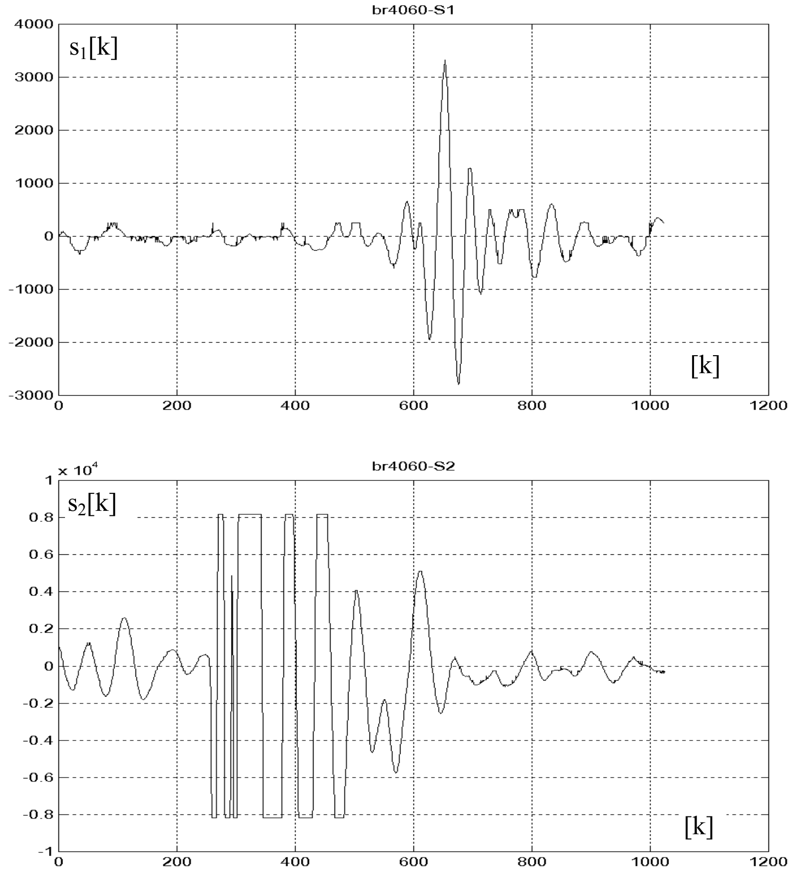
$$V = \frac{L_2}{\Delta t_2} = \frac{20m}{125.5 \cdot 10^{-3} s} = 159.36 \frac{m}{s} \tag{10}$$

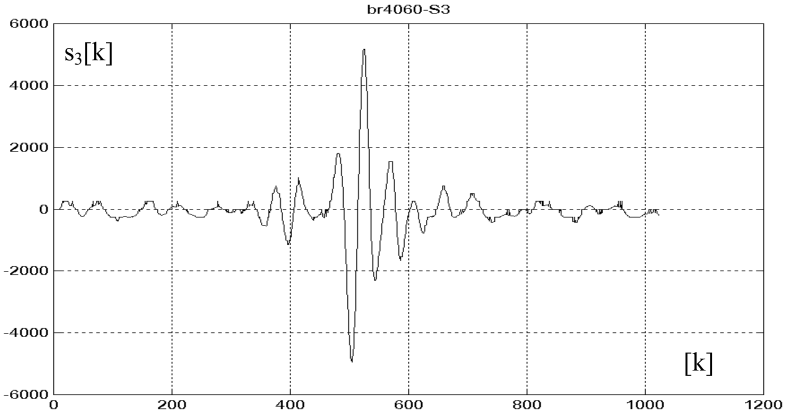
The average seismic wave propagation velocity on the terrain of the hunting ground "Karadjordjevo" equals 159.36 m/s. For the comparison of the obtained results of the calculated propagation velocity an additional measurement was performed. The distribution of the sensors on the terrain and the point of the impulse excitation are shown in Figure 6. The excitation source is in the sensor S2, and the distance from the sensor is L_2 = 40 m. The distance between the sensors S1 and S3 remains the same as in the previous experiment and equals L_3 = 20 m. The signal saturation in the sensor S2 is quite clearly discerned from the figure as the location of the excitation is near the sensor. The time shift of the peak in the signals from sensors S1 and S3 can also be observed in the figure. The calculation of the seismic wave propagation velocity was obtained according to the relation (10). By finding the average value of the calculated velocities, the obtained value of the velocity of the seismic wave is V = 156.25 m/s.

Because of the signal saturation in the sensor S2, it is not convenient to use this signal for the calculation of the time delay. For the calculation of the time delay, the signals from the sensors S1 and S3 are used. The signal time delay is determined by locating the peak in the cross-correlation function obtained by the correlation of the signals from these sensors, which is, once the distance between the sensors is known, enough for the determination of the seismic wave propagation velocity through the real geological medium.



a)





b)

Fig. 6. a) Experimental constellation of sensors and the location of excitation;
b) Waveform of the signal when the location of excitation is near the sensor S2.

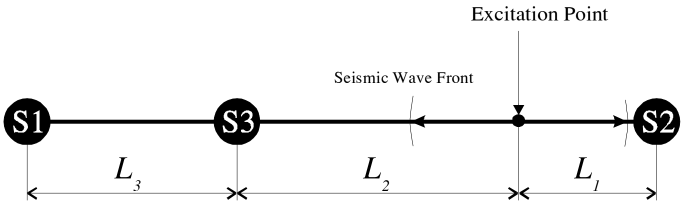


Fig. 7. Sensor constellation for the multiple calculation of the propagation velocity of the seismic wavefront

In Figure 7, the location of the impulse excitation and the geometrical constellation of the sensors which enables the multiple calculation of the seismic wave propagation velocity are shown. In a system like this, it is possible to calculate the seismic wave propagation velocity for three different ways that the seismic wavefront passes. In this case, the average velocity is adopted:

$$V = \frac{V_1 + V_2 + V_3}{3} \ ,$$

where the partial velocities on different sections are calculated as:

$$V_1 = \frac{L_3}{\Delta t_2},$$

$$V_2 = \frac{L_2 - L_1}{\Delta t_3},$$

$$V_3 = \frac{L_2 - L_1 + L_3}{\Delta t_1}.$$

The propagation velocities of seismic waves [1] through different types of geological media are given in Table 2. The seismic wave propagation velocity varies from 100 m/s on the horizontal humus terrain to 6800 m/s in the marble.

Table 2. The propagation velocities of seismic waves through different types of geological media

MEDIUM	Velocity [m/s] min	Velocity [m/s] max
Air depending on temperature	310	360
Weather soil horizon	100	500
Gravel, dray sand	100	600
Loam	300	900
Wet sand	200	1800
Clay	1200	2500
Water depending on temperature	1430	1590
Sandstone friable	1500	2500
Sandstone dense	1800	4000
Chalk	1800	3500
Limestone	2500	6000
Marl	2000	3500
Gypsum	4500	6500
Ice	3100	4200
Granite	4000	5700
Metamorphosed rock	4500	6800

5. CONCLUSIONS

By analyzing the obtained signals for such distribution of the sensors, a very important fact can be observed. Different resonant frequencies appear in the spectrum of signals from particular senzors. The differences in the resonant frequencies of the sensors can have a negative influence on the algorithm for the calculation of the delay time. For these reasons it is necessary to add an algorithm for the calculation of the time of delay between the signals so that the control of the resonant frequencies for the given sensor and for the given excitation can be performed. Different resonant frequencies may occur when the signals in the sensors originate from several excitation sources. By inspection of the calculated delay times for this case, it is obtained that these times were calculated correctly, while the real delay times are quite different. By checking the resonant frequencies for the detected signals we conclude that they are different, which means that the obtained results for the delay times are incorrect. Therefore, the obtained results for the delay times should be discarded because they cannot be used for the calculation of the exact location of an unknown seismic wave source. There is a theoretical possibility to obtain the more precise delay time by the correction of the obtained numerical values in proportion to the dominant frequency in the spectrum of each sensor. This possibility is not dealt with in more detail in this paper and will be the issue of further investigations. The examples when the dominant frequencies of the signals differ for the same excitation were obtained in the conditions of high geological interference in the case of the strong wind. To solve the problem of the location of the seismic wave source in space, it is necessary to know the seismic wave propagation velocity in the directions from the excitation source to the sensor.

For the distributions of the sensors in the angles of the equilateral triangle the first point for which the verification of the homogeneity of the measured terrain is performed is its center. In an ideal homogenous medium the signal delay in all the three sensors should be equal, i.e. the difference in the delay times should equal zero. In practice, no absolutely correct results are obtained and the delay equals from 1 ms to 2 ms at the sampling frequency of 1 kHz. With the geological terraines of this property, it is not necessary to measure the propagation velocity in each direction. It is enough to do it for only one direction. In the case when the delays cannot be ignored, it is necessary to make measurements in all directions. From the obtained excitation location coordinate of the seismic wave for the average velocity, it is necessary to correct the coordinates according to the calculated velocities for each direction.

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MERENJE BRZINE PROPAGACIJE SEIZMIČKIH TALASA U REALNOM MEDIJUMU

Vlastimir D. Pavlović, Zoran S. Veličković

U ovom radu opisana je efikasna tehnika određivanja brzine propagacije seizmičkih talasa u realnom geološkom medijumu. Brzina propagacije seizmičkih talasa varira u zavisnosti od tipa geološkog medijuma i nalazi se u opsegu od 100 m/s do 6800 m/s. Zbog toga je neophodno da se odredi propagacija fronta seizmičkih talasa između različitih tačaka u realnom medijumu. Kašnjenje signala je odredjeno lociranjem tipa kroskorelacione funkcije dobijene korelacijom senzorskih signala. Efikasnost metode je ilustrovana eksperimentalnim rezultatima.