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CROSS HOLE ZONDING USING SH-WAVES – PRELIMINARY RESULTS

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The results of cross-hole sounding experiment are presented for new calibrated source of SH-waves mounted in the well. Seismic response was recorded by the vector receiver dipped into various depths with the step less than shear wavelength for maximal radiated frequency. The source coherence allowed the signals accumulating that provided the signal-to-noise ratio increase by 20 dB improving seismograms significantly. The comparison of the seismograms obtained with the use of surface and dipped sources of different types was made for the same measurements geometry. The absence of exchanged waves was proved for both surface and dipped vibrators excited SH-waves. Benefits of sounding used the dipped SH-wave source are discussed.

In paper [1] we have compared seismoacoustic characteristics of vibratory sources with horizontal and vertical force vector applied to the ground surface. Portable vertical vibrators are used widely for the excitation of seismic waves and are described in [2, 3]. The main area of the portable vibrators application is the engineering seismic survey for building construction, the searching for underground engineering structures, communications, karst cavities etc. [4]. It should be noted that horizontal vibrators are used relatively rarely. To excite seismic waves in cross-hole profiling monopole sources (e.g. electrospark type) are usually used [5]. Sometimes explosive sources are used [6]. Vector sources in cross-hole profiling are almost not used due to complexity of their realization.

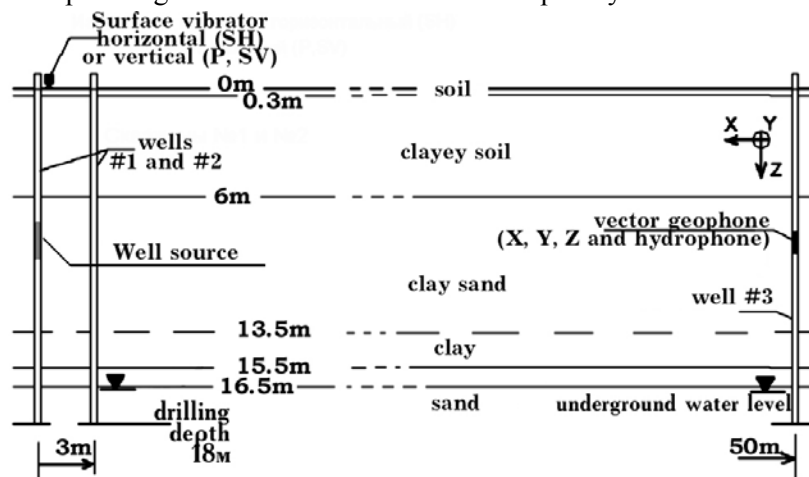


Fig. 1. Approximate log at the place of measurements. Data correspond to geological survey distanced by 500 meters from the test site.

We developed force (vector) source based on the flexural vibration excitation of the steel cylinder put in a well [7]. In this paper we show seismoacoustic characteristics of the source like [7] dipped in the well and surface vibrators of vertical and horizontal force vector. All results were obtained for similar conditions and within the same geometry in IAP test site "Bezvodnoe" in 2004 and 2007. The geometry of measurements is shown in Fig. 1. We used two wells of 15 meters depth filled with water. Vector accelerometer was put in the well #3 (Fig. 1). The accelerometer depth was incremented by 1 meter during the measurements. Other well (#1 in Fig. 1) distanced by $d = 50$ meters from the receiving well was used to put the source. The steel cylinder of 1.57 meters length was centered at $z_0 = 7.7$ meters depth. The cylinder was flexing in the plane perpendicular to the line connecting two wells. Surface vibrators were set on the ground close to the well #1 (see Fig. 1). Geology structure shown in Fig. 1 corresponds to data obtained during drilling of the well for drinking water supply. That well is located 500 meters from the well #3 and, therefore, the log depicted in Fig. 1 reflects expected or approximate structure of the layers at the place of measurements.

The signal of linearly modulated frequency was used as a probe signal. The frequency band was 60-200 Hz for surface vibrators and 60-170 Hz for the source dipped in the well. High stability and coherence of the received signals allowed measuring the field structure using one receiver under preserving amplitude and phase relations [4]. Fig. 2 depicts impulse responses for surface vibrators. Impulse responses were calculated standard [8] using inverse Fourier transform for complex transfer function (ratio of acceleration to the pilot electrical signal).

Force source oscillated normally to the ground surface generated both longitudinal and shear waves of vertical polarization (SV-waves) [9, 10]. When these waves propagated through vertically stratified medium exchange waves are generated when waves are reflected by layer boundaries (transformation

of the longitudinal wave to the shear one and vice versa). The vibrator oscillated parallel to the ground surface radiated shear waves of horizontal polarization (SH-waves) in the direction normal to the displacement vector of the baseplate [1]. Shear wave of horizontal polarization is a self-consistent solution for vertically stratified medium and no exchange waves were generated under reflection [5]. This is clearly seen in Fig. 2.

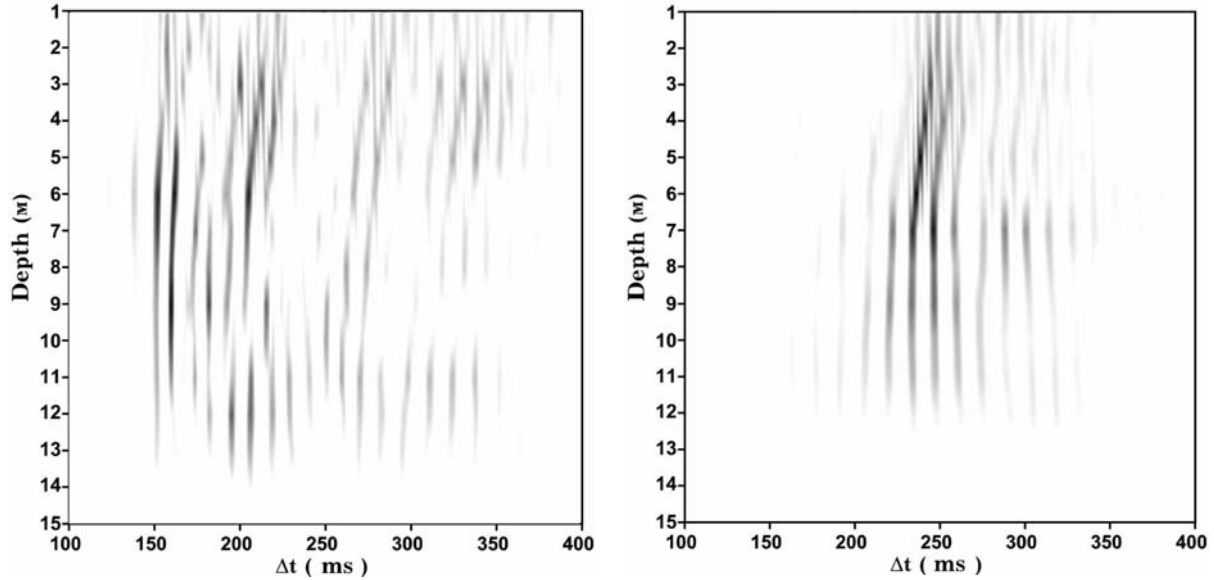


Fig. 2. Impulse responses measured in the similar conditions for vibratory sources of seismic waves. At left the data for the source of SV- and P-waves (vertical vibrator) are shown. At right the data for the source of SH-waves are shown. Brightness is normalized to maximal intensities for each experiment. Only positive half waves are shown to make the patterns more contrasted.

For the receiver depth of 5-10 meters the arrival time of P-wave is $\Delta t_p \approx 150$ ms that corresponds to propagation velocity of $V_p = 333$ m/s. Shear wave arrive to the point of observation with the delay of $\Delta t_s \approx 230$ ms (the most clear it is seen in Fig. 2 at right) that corresponds to the propagation velocity of $V_s = 217$ m/s. Comparing impulse responses of vibratory sources of vertical and horizontal force vector we see the absence of exchanged waves with delays $\Delta t_p < \Delta t < \Delta t_s$.

In Fig. 2 we clearly see that for SH-waves radiation the arrival numbers are much less than for P- and SV-waves radiation. The intensity of arrivals becomes higher also for the source of SH-waves. The number of arrivals in the case of vertical vibrator (the radiation of P- and SV-waves) is increased because during the reflection of P- or SV-wave at a boundary between layers two reflected and two refracted waves are generated contrary to the case of SH-wave when only one reflected and one refracted waves are generated. As a result of such coupling between P- and SV-waves the number of arrivals is increased while their intensity is decreased. Data presented in Fig. 2 are also in a very good agreement with impulse responses obtained using tonal-impulse signals [1].

Impulse response of the dipped source put in the well at 7.7 meters depth is shown in Fig. 3. The data in Fig. 2 at right and in Fig. 3 at left revealed the resolution improvement for the source dipped in the well comparing with the surface vibrator for approximately the same radiated frequency band. It is presumably due to stronger attenuation in upper soil layers when the waves were radiated by the surface vibrators. The propagation time of SH-waves for both surface and well sources is the same within impulse width. Thus, we can see the absence of systematic errors in measurements made in different times using different types of the sources of seismic waves.

The data in Fig. 3 at left also revealed interesting peculiarity which allows additionally proving the absence of errors. At the depths up to 5 meters we see wave fronts of the slope corresponding to the reflection at the ground surface. The sign of displacement is not changed in the reflected SH-wave and phase difference between direct and reflected rays is $(z, z_0 \ll d)$

$$\Delta\varphi \cong \frac{4\pi f z_0 z}{V_s d}, \quad (1)$$

where $f = 120$ Hz is the central frequency radiated, z is the receiver depth, $V_s \approx 222$ m/s is the SH-wave velocity (numerical value corresponds to the averaged over the depth in Fig. 3 at right). At the depth of 3 meters the phase difference (1) becomes equal π and positive displacements in the reflected wave lies strictly between those corresponding to the direct wave. This is clearly seen in Fig. 3 at left.

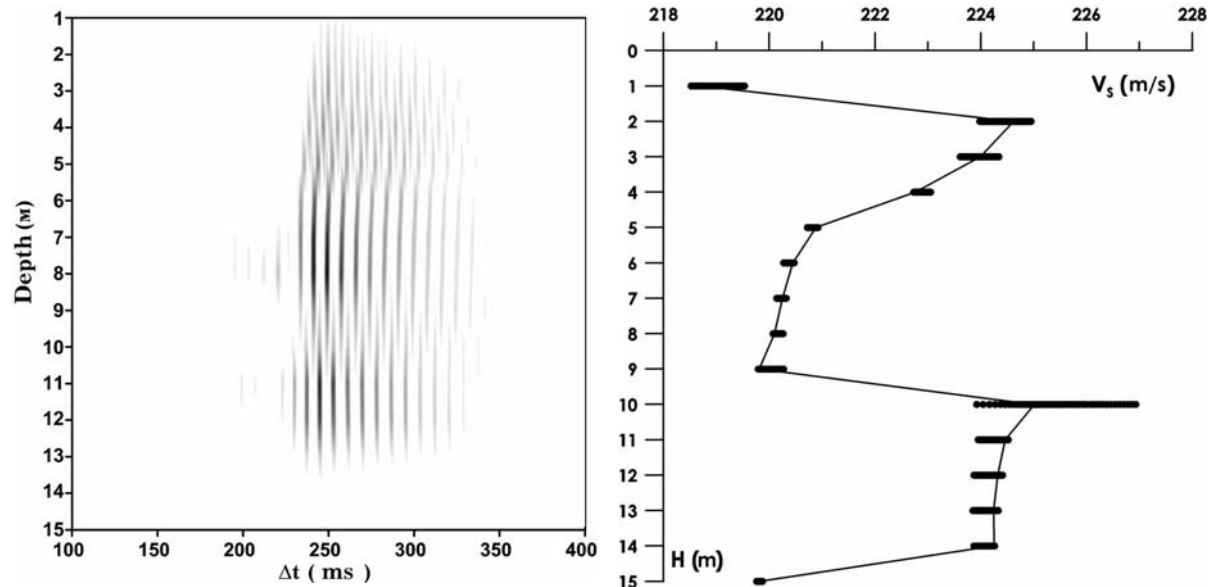


Fig. 3. At left the impulse response is presented for the dipped by 7.7 meters depth source. As for data in Fig. 2 only positive half-waves are shown. At right the velocity profile is presented. The profile is reconstructed using phase-frequency dependences in the band of 100-130 Hz.

The distance between the source and the receiver is varied a 1% only when the receiver depth is changed within ± 7 meters. The phase variations occur in wider limits than the arrival time that allows adjusting the velocity of SH-wave. In Fig. 3 at right we present the SH-wave velocity profile within the layer of 15 meters thickness. Here we should point out that phase method is used only occasionally in profiling [5, 11] because the absence of the long time stability of the phase between the source and the receiver. Initial impulse responses were gated so only times between 200 and 350 milliseconds were analyzed. The sounding signal is localized right within these limits (see Fig. 3 at left). Then impulse responses were transformed into the frequency domain. The delay of 225 ms for the first arrival at the depths of 5-9 meters was accounted and small perturbations of 2 ms due to the change of the distance between the source and the receiver were accounted also. For each frequency in the spectra the spatial filtering procedure was made [11] that reduced the contribution of the waves arrived with the grazing angles more than $\pm 10^\circ$. These angles corresponded to the ground surface reflection (Fig. 3 at left). High coherence in the frequency band of 100-130 Hz was obtained using accumulation [4]. The analysis of the phase differences versus the receiver depth allowed revealing small variations in phase. These variations were associated with the changes in shear wave velocity. The phase differences in Fig. 3 at right were calculated relative mean value for the receiver dipped at 6-9 meters depth. Obtained values of the SH-wave velocity correspond to the averaged over the wave propagation path [11]. As the relative velocity variations are small a correction accounting the length of the propagation path in different layers as well as possible change of angles after the wave refraction is not required.

It is interesting to compare the velocity profile obtained with known log data depicted in Fig. 1. The log was drawn after geological work made at 500 meters from the test site. We can distinguish boundaries at 1-2, 5, 10 and 14 meters depth (Fig. 3 at right). The velocity decrease in upper layers above 1 meter depth was observed in the field experiment [12] where shear wave velocity was measured as small as 150 m/s. The boundary of 1-2 meters can be associated with the transition from loose grain contact in soil at the ground surface to clayey soil with grain appressed by the weight of upper layers. Clayey soils consist of 10-30% clay particles [13] which filled the space between sandy grains. Clays going dry are natural cements. It explains why the layer at 2-5 meters depth has shear wave velocity higher than the layer of clay sand at 5-10 meters depth. Clay sand contains less amount of clay particle

between sandy grains than clayey soil [13]. The contrast boundary at 10 meters depth is clearly seen (Fig. 3 at left). This boundary presumably corresponds to the transition between clay sand and clay. Small size of clay particles makes for the clay consolidation [13] and shear modulus (shear wave velocity) increase. At the depth of 14-15 meters due to water table shear strength is decreased.

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