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The surface waves-based seismic exploration of soil and ground water

AS Serdyukov¹,², AV Yablokov¹, GS Chernyshov¹ and AV Azarov²

¹Institute of Petroleum Geology and Geophysics, Siberian Branch, Russian Academy of Sciences, Novosibirsk, Russia
²Chinakal Institute of Mining, Siberian Branch, Russian Academy of Sciences, Novosibirsk, Russia

E-mail: ¹serdyukovas@ipgg.sbras.ru; ²antonazv@mail.ru

Abstract. We consider the method to study physical properties of soils. The new seismic exploration approach, based on new modification of refracted wave plus-minus method and multichannel analysis of surface waves (MASW), is proposed. We present the field data processing example. The ground water level and zones of erosion are detected.

1. Introduction
For geotechnical investigations and assessment of pitwall stability, the study of physical and mechanical properties of rocks and soils in situ is required. First and foremost, it concerns dispersive soils. It is possible to determine physical and mechanical properties of cohesive dispersive soils with the help of seismic exploration. According to the studies [1, 2] P- and S-wave velocities can be used for the geotechnical investigations. The primary properties defined by the regulations of the investigations are: soil moisture $W$, yield point $Wm$, soil density $\rho$, matrix density $\rho_m$ and deformation modulus $E_m$. All mentioned properties can be determined with adequate accuracy from the velocity profiles of P- and S-waves [3]. Correlation formulas for typical cohesive dispersive soils (sandy loam, loams, clays, etc.) derived by regression analysis are presented in methodological recommendations [4].

For seismic shallow investigations spread line system with one-component sensors is typically used to register vertical oscillations on the daylight surface. Pulse percussion sources cause the oscillations. It is possible to induce and register the transverse oscillations with the suggested scheme, but it is inconvenient due to the following reasons. Thus, the low-velocity zone is characterized by sudden changes of the elastic properties and density as well as the contrasting refracting boundaries. It is difficult to assess the influence that complex medium features have on dynamic properties of seismic waves; therefore, predominantly kinematic methods are used for the wave studies [5–7]. As a rule, seismograms show the easily distinguished first arrivals of P-waves, including the arrivals of direct waves close to the source, and refraction waves at a distance from the source. It is complicated to employ reflected waves because they are rare distinguishable from the surface waves with larger amplitude [8].

The standard method of one-component data processing in geotechnical investigations is to restore velocity profile of P-waves using refraction method, P-waves velocities are estimated by Knopov charts [4]. In the classical algorithms [9] the depth of the refracting boundaries is determined, and
velocities between layers are constant. On the basis of the data on head waves velocities distributions along a refracting boundary are reinstated. The direct wave data help to restore average velocities in near-surface layer. Practically there can be lateral changes of P-wave velocities, for example, changes due to moisture. When constructing the velocity profile using the classical method \( t_0' \) (“plus–minus” method) heterogeneity areas of hodographs correlating with the top layer are interpreted as the changes in the reflecting boundary depth [10]. The heterogeneity may be covered by lateral perturbations in velocity distribution of a P-wave in the top layer. In order to adjust the heterogeneity a priori information has to be employed. This paper discusses a typical case in which the boundary coincides with the ground water level, and only gradual changes of refraction depth is implacable. Therefore, it is necessary to even the boundary by equivalent velocity perturbations in the top layer. In this work we have implemented the described idea by means of the modified refraction method \( t_0' \).

To build a velocity profile of S-waves we use multichannel analysis of surface waves (MASW) [11] instead of Knopov pattern. The main point of this approach is reduced to the construction of a stratified model based on the dispersion curves of the Rayleigh wave phase velocity.

2. Modified refraction method

Refracted wave \( t_0' \) method, known abroad as “plus–minus” method, is presented in the literature in details [10]. While using the method to process field data of shallow seismic investigations the form of the restored boundaries is usually not smooth with the small local depth drops. From physical standpoint these frequent changes are unlikely to happen, for example, the level of the upper groundwater may gradually change, but frequent small irregularities are not typical.

Let us consider the case when the velocity of the first layer, which is determined by the direct wave travel time, is not precise. In field measurements this situation may be the result of a number of reasons: the low frequency of the probing signal, low power of the near surface layer, seldom arrangement of the detectors, the irregularities in the bottom of the layer. Then, the perturbations of the refracting boundary \( \delta h \) depth and P-wave velocity variations in the upper layer \( \delta V_1 \) are connected as

\[
\delta h = \frac{T_D \delta V_1}{2\cos^2 \theta}, \quad (1)
\]

where \( T_D = T_{AD} + T_{HD} - T_{AD} \) — expression composed of travel times of the head wave, \( T_{AD}, T_{HD}, T_{AD} \) — travel times between the corresponding points (Figure 1). Using formula (1) one can interpret minor departures from the depth smoothness of a bearing boundary, defined by the classical method \( t_0' \) as the velocity variations in the upper layer.

![Figure 1. Linear scheme of seismic wave propagation.](image)

The suggested method involves the following steps: firstly the classical method \( t_0' \) is employed, then, the found boundary is smoothed, and the difference between the initial and smoothed depths is inserted into the formula (1) to make the velocity in the upper layer more precise. Supposing that the perturbations are minor, the formula (1) is obtained due to linearization, and it is more efficient to use the formula in several steps (gradually smoothing the boundary). In accordance with this principle, the depth-gradient model is built for every move-out.
2. Multichannel analysis of surface waves

The next step of data processing is transition into spectral f-k domain. Two-fold Fourier transformation is applied to the seismogram in respect with a measuring points offset coordinate and with time. Then, there is transformation of f-k (1/s-1/m) figure into the dependence domain of Rayleigh wave phase velocity on temporal frequency V-f (m/sec—1/sec). There is a high level of signal/noise ratio due to the fact that not less than 2/3 of the energy is spent on the surface wave formation while oscillations are induced. The dispersive curves are obtained by setting the amplitude maximums in the observing frequency range depending on the seismic profile length, distance between the seismometer, seismogram recording length and sample spacing.

Re-establishment of the S-wave velocity profile is based on the adjustment of the layered one-dimensional model (of S-wave velocity) using the dispersive curve and repeated solving of the primal problem. Next, we implement interpolation of one-dimensional profiles in order to get 2D (or 3D) models of the geological cross section under the survey. The prime problem is solved in the one-dimensional model of the medium consisting of horizontal plane–parallel homogenous isotropic layers. Their phase velocity dependence on the frequency (dispersive curve) can be found analytically, by finding eigenvalues for displacement–stress vector [12]. We use a modified matrix propagator method, the so-called “method of reflection and transmission coefficients.” Then, we search for the minimum of residual functional between the observed and calculated dispersive curves. Minimization is performed with the help of Levenberg–Marquardt algorithm, which is a modification of the Newton method [13].

3. Interpretation methods of velocity profiles and analysis of dispersive cohesive soil properties

It is possible to interpret medium boundaries comparing $V_p$ and $V_S$. S-wave velocities, unlike P-wave velocities, do not undergo jumps at the groundwater boundaries [4]. If there are lithological boundaries above the ground water level $V_p$ and $V_S$ changes are observed. In case when lithological boundaries are below the ground water level there are jumps of $V_S$ while there are subtle changes in $V_p$ [4]. Therefore, it is very important to use relevant geological information as well as geoelectric data. Characterization of physical and mechanical properties of cohesive dispersive soils is based on correlation dependence given in methodological recommendations [4]. The presented formulas are applicable for the soils above the ground water level with less than 30% moisture. If the soil is greatly saturated, P-wave propagates along the liquid, and its velocity weakly depends on rock matrix properties. To calculate moisture $W$ and matrix density of the rock $\rho_{\text{ex}}$ we have employed iterative updating procedure of values. At first, the rock density is estimated approximately $\rho_{\alpha} = 1,38 + 0,00033 \, V_p$, where velocity is measured in m/sec, and density is measured in g/cm³. In what follows empirical constants have the corresponding degrees. The calculated matrix density is used to measure the moisture

$$W = 79,06 - 0,00382 \, V_p - 30,1 \, \frac{V_S}{V_p} - 28,91 \, \rho_{\text{ex}}.$$  \hspace{1cm} (2)

The moisture is measured in percent of the mass. Calculated by the formula (1) moisture is used to get a more precise value of the matrix density

$$\rho_{\text{ex}} = 2,34 - 0,736 \, \frac{V_S}{V_p} - 0,0245 \, W.$$  \hspace{1cm} (3)

The specified matrix density is inserted into the formula (1) and etc. The conducted numerical experiments prove that for typical P- and S-wave values iteration process (1)–(2) converges in 10 iterations. The process is stopped if the absolute values of difference between the values in two last iterations do not exceed tenth of percent of the last iteration values.
An important physical parameter is the yield point $W_m$. It is moisture due to which soil state turns from plastic condition to liquid one. The yield point is calculated using the formula

$$W_m = 36.93 + 0.8W - 13.143\rho + 0.0429V_s.$$ 

The calculated matrix density and yield point values allows estimating the deformation modulus

$$E_0 = 0.0549V_p + 0.666V_s + 145.4\rho_{\text{sc}} + 20.66(W_m - 27.8)(\rho_{\text{sc}} - 1.56) - 266.1,$$ 

characterizing compression (elastic and plastic parts) of soil in case of static (quasistatic) vertical loadings. It is possible to determine other characteristics [1, 4].

4. Field data processing results
Shallow seismic investigations have been carried out in the suburb of Novosibirsk on the 8th of October 2015 along the road Akademgorodok–Klyuchi, Kamenshuka river. The distance between the detectors of the linear observing system is 1 m. One-component vertical seismic receivers with 10 Hz frequency are used. Source points are placed along the observation line at a 5 m distance from each other. To induce oscillations in all the points a 5 kg sledgehammer is used to hit a metal base. Figure 2 shows the constructed P wave velocity profile. At the 4 m-depth we have found the underground water line. The top of Figure 2 presents the velocity profile constructed using the well-known method $t_p'$. At the bottom of this figure, there is a velocity profile derived by the suggested modified method.

**Figure 2.** P-wave velocity profiles: at the top—obtained by the standard method; bottom—by the modified method.

Figure 3 shows the S-wave velocity profile resulted from the multichannel analysis of surface waves. Comparing S- and P-wave velocity profiles we have come to the conclusion that the observed line in Figure 3 marks the ground water level. Smoothness of the line is caused by the physical properties, and it shows the efficiency of the developed method.

**Figure 3.** S-wave velocity profile.

Figure 4 introduces the restored soils properties distribution down to a depth of 3.5 m. At the top of the figure there is the ratio between the yield point and moisture. The values close to 1 are the indicators of transformation into liquid state in case of a slight moisture increase. At the bottom of the figure there is general deformation modulus characterizing soil compressibility. Areas with the low values of the modulus are more likely to be deformed. Areas of concern are settlements on the 12–24 m of the profile and quick grounds at 43–56 m of the profile. They correlate with the changes of properties in Figure 3. The obtained results are in agreement with the road observation which proves the effectiveness and efficiency of the suggested method.
5. Conclusion
For geotechnical investigations we have developed a seismic method based on the concurrent processing of the first P- and S-wave arrival times. The suggested method based on correlating dependences makes it possible to restore physical and mechanical properties of cohesive dispersive soils and to determine areas subjected to deformation and erosion.

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