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SUBSOIL CHARACTERIZATION WITH USE OF ACOUSTICAL METHODS

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ABSTRACT

In a homogeneous half-space the ratio of amplitude of horizontal projection of displacement to the vertical one is a function of Poisson's ratio. It thus can be assumed that the dependence of this ratio on a frequency could assess the Poisson's ratio profile in a vertically layered medium. Based on this fact we have developed the SASW ("Spectrum Analysis of Surface Waves") method by considering the frequency dependence of the projections ratio. Along with the shear wave velocity profile one can thus recover pressure wave velocity profile. Water saturation effects on the medium characteristics were studied based on this technique.

1 INTRODUCTION

Liquid situated in the soil's pores has a strong impact on its characteristics. A high water content may lead to change in the strength properties and, in particular, to dilution of the soil. Therefore, in order to predict disastrous events one needs to be able to conduct remote diagnostics of the degree of saturation. Diagnostics of the degree of saturation and fluid distribution in space is also of interest for environmental applications related to the assessment of the degree of soil contamination with oil products, etc.

In the engineering seismic survey it is widely used the method of spectral analysis of surface waves [1,2] (abbr.: SASW). The method has become popular for several reasons: (1) the ease of implementation, (2), characteristics of direct wave are analysed, (3) when placing the seismic source on a surface, the Rayleigh wave has the highest energy among the other generated waves, what simplifies its extraction in the wave response of the medium. In the standard realization of the SASW method for medium's parameters reconstruction the Rayleigh wave dispersion chararacteristic is used solely, what allows determining only the shear wave velocity

It is known that in homogeneous half-space the ratio between amplitudes of horizontal displacement projection and vertical one is a function of Poisson’s ratio and monotonically increases from 0.54 to 0.78 when decreasing the Poisson’s ratio from 0.5 to 0 (e.g. [3]). It was assumed and then clearly shown [4,5] that the dependence of this ratio on frequency provides sufficient knowledge about the distribution of Poisson's ratio in a vertically stratified medium, and the inverse problem solution in the case of considering variations of this parameter becomes more correct. Therefore we have modified the SASW method by taking into account the frequency dependence of the ratio of horizontal and vertical components of displacement in the Rayleigh wave along with the analysis of the dispersion characteristic. As far as we can judge on the basis of the known literary sources, such studies were not conducted before.

2 EXPERIMENT AND DATA PROCESSING

Figure 1 depicts the general scheme of measurements. Seismic waves were launched by a vertical vibrator (designed in the Institute of Applied Physics) mounted on the surface of the soil and creating a vertical force directed downward. The vibrator was excited by the signal with linear- frequency modulation (LFM signal) in the frequency range 5-200 Hz. The analog signal was synthesized by DAC manufactured in “National Instruments”. The reception was carried out with use of vertically and horizontally oriented geophones placed in pairs. The total number of geophones was 48. The distance between pair’s positions was set up to be 0.5 m. Thus the receiving array was created. The distance between the vibrator and the closest pair of geophones exceeded one-sixth of the maximum wavelength and satisfied the far field conditions for all receivers. The signals were recorded by two 24-digit seismic stations “Lakkolit X-M2” (designed in "Geotech", Moscow). The recording time of one realization was 3072 ms, each set of measurements consisted of 100 and more realizations, which were then coherently summed in order to increase the signal-to-noise ratio.

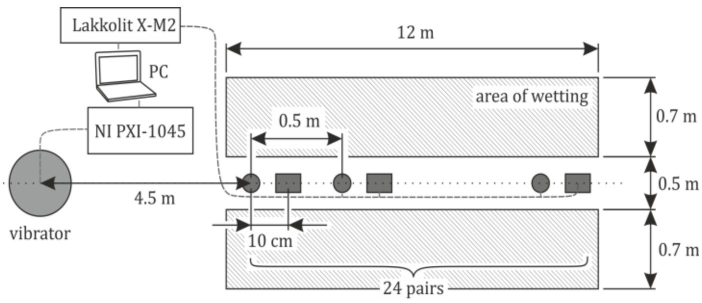

Figure 1. The source and receiving array (on the left). General scheme of measurements (on the right). Small circles and rectangles correspond to the positions of vertically and horizontally oriented geophones respectively, a large circle – to the position of the source.

The test area (shaded on the scheme in Figure 1) was uniformly saturated with water in the known volume. The dependence of the volume of water being poured on time is shown in Figure 2. In order to avoid spreading of water the upper layer of the soil was loosen at a depth of 5 cm prior to the experiment implementation.

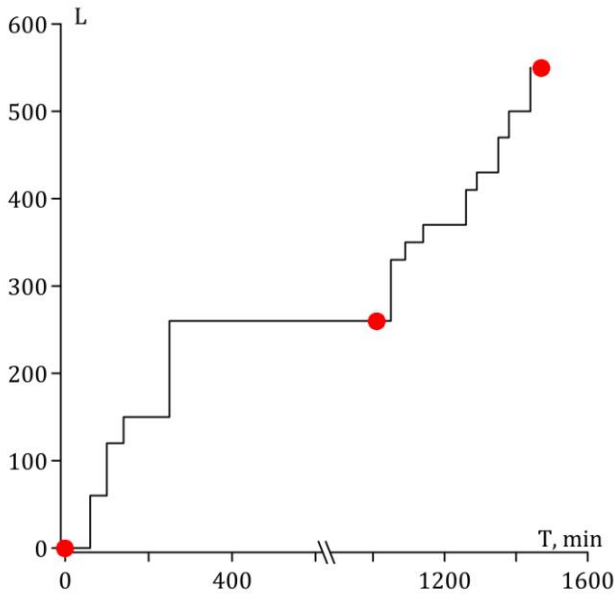

Figure 2. The dependence of the volume of water being poured on time. Red dots depict instants of time, for which profiles in Figure 4 are given (see below). During the night measurements were not carried out what is represented as a gap on the time axis.

To extract the Rayleigh wave from the wave packet recorded by the receiving system and to determine its dispersion and the displacement projections ratio the procedure of the analysis of spatial and temporal frequencies (F-K analysis [6,7]) was implemented. The spatio-temporal spectra which arise by a transition from spatio-temporal domain (t,x) to a domain of spatial and temporal frequencies (f,k) with use of two-dimensional Fourier transform, are shown in Figure 3. On the spectra obtained from horizontal and vertical receivers the characteristic lines corresponding to the Rayleigh wave were derived. Their slope determines the phase velocity. The projections ratio was calculated by division of spatio-temporal spectra in points corresponding to the Rayleigh wave contribution.

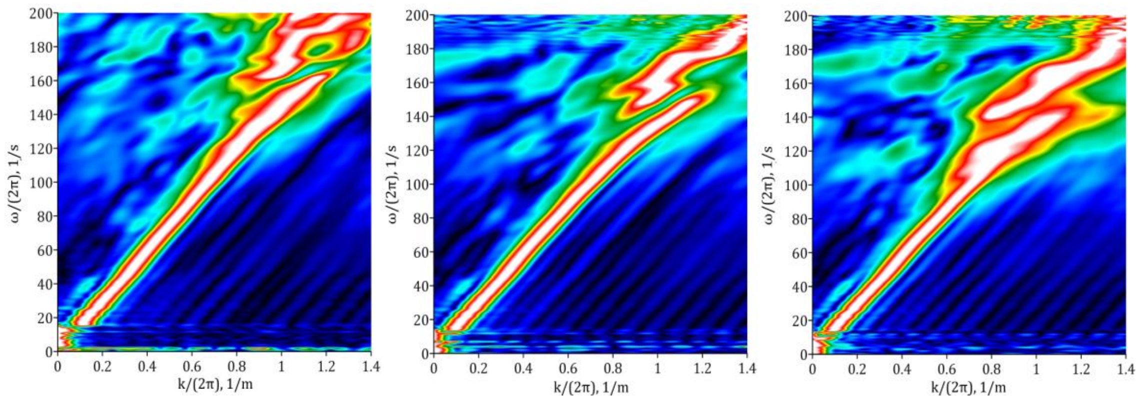

Figure 3. Spatio-temporal spectra derived as a result of processing the data received from vertical geophones. The picture on the left corresponds to the initial state of the soil, in the center – to the beginning of the second day of measurements, on the right – to the end of the second day.

The dependencies of the Rayleigh wave phase velocity and the projections ratio on frequency are shown in Figure 4. At frequencies above 120 Hz the ratio of the projections amplitudes is strongly perturbed due to the presence of loosened surface layer, and therefore the data for this frequency range are not shown and were not analyzed.

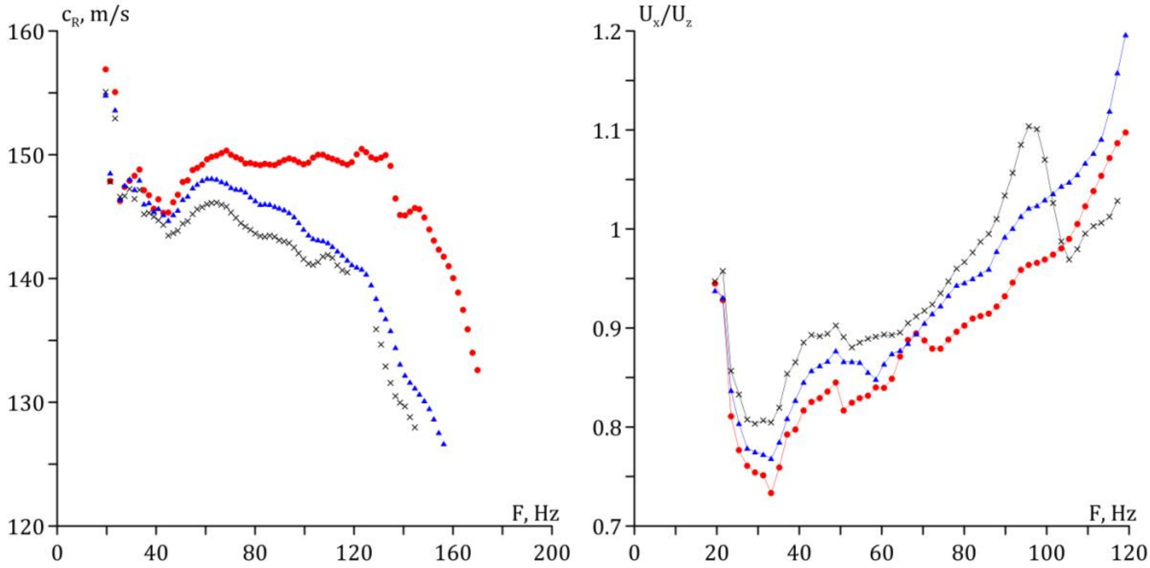

Figure 4. The frequency dependencies of the Rayleigh wave phase velocity (on the left) and the ratio between amplitudes of horizontal and vertical projections of displacement (on the right). Red color corresponds to the initial state of the soil (after loosening but before pouring the water), blue – to the state of the soil at the beginning of the second day of measurements, black – to the end of the second day (when the experiment was finished).

3 INVERSE PROBLEM SOLUTION

When solving the inverse problem the model of plane-layered medium was considered. This model takes into account the existing spatial homogeneity in the experiment site. Unknown parameters were the velocities of longitudinal and shear waves and the thicknesses of layers. The search for optimal parameters was carried out using both stochastic and deterministic algorithms. As a stochastic method it was the genetic algorithm [8], and for the adjustment of the results obtained – the Nelder-Mead method [9]. The typical dependencies of the Rayleigh wave phase velocity and the ratio between amplitudes of horizontal and vertical projections of displacement derived as a result of inversion are shown in Figure 5.

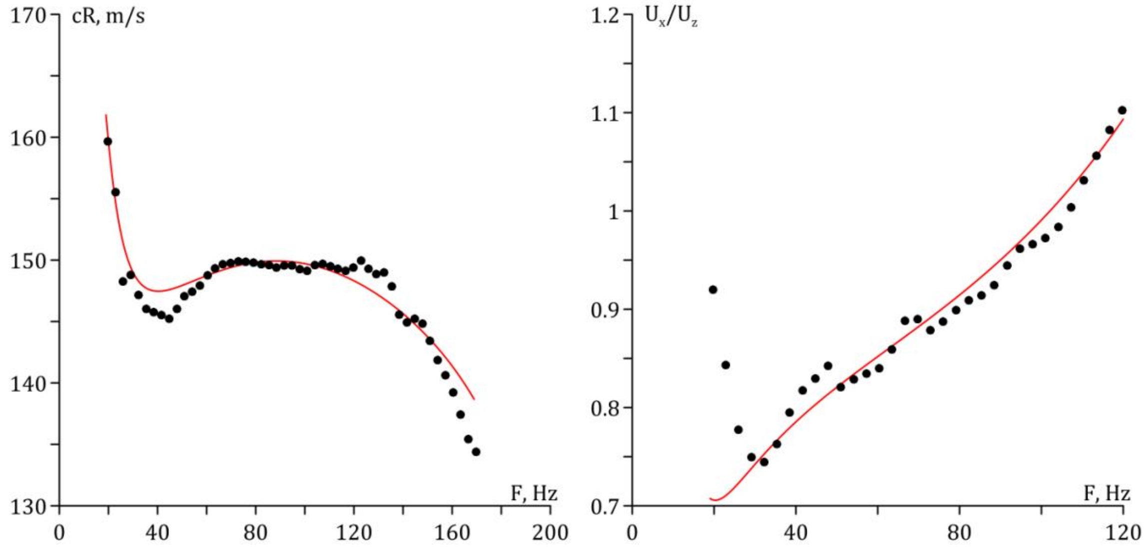

Figure 5. The frequency dependencies of the Rayleigh wave phase velocity (on the left) and the projections ratio (on the right) at the initial moment of experiment's implementation (before adding a water). Black dots image the measured data, red lines correspond to the result of inversion. The bend in the plot of the frequency dependence of the projections ratio in the vicinity of 20 Hz is presumably associated with the near field effects.

Parameters of the medium resulting from the inverse problem solution are presented in graphical format in Figure 6. For the upper layer during the saturation the shear wave velocity decreased and the longitudinal wave velocity increased. This is because the water breaks the bonds between grains, what leads to decrease in the shear stiffness. At the same time it facilitates the increase in the compression stiffness as fluid has a bulk modulus greater than one of the skeleton. For underlying layers the variations are more complex and presumably related to the filtration of fluid downwards (second layer) and the appearance of capillary forces, leading to an increase in the stiffness of porous medium (third and fourth layers). These features and the possibility of their use for the purposes of diagnostics of fluid content in pores are the subject of further study, which is supposed to be carried out not only in-situ but also in the laboratory conditions for the adjustment of description.

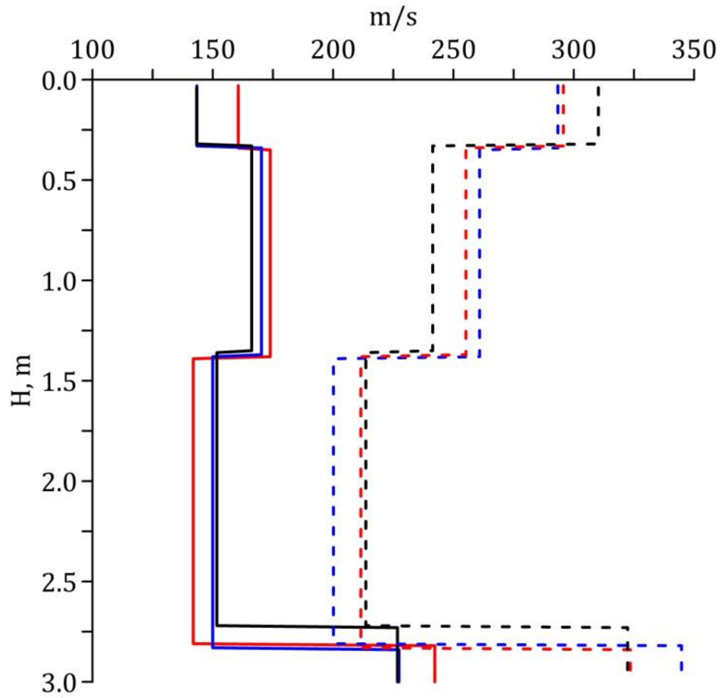

Figure 6. The reconstructed velocity profiles. Red color corresponds to the initial state of the soil, blue – to the state of the soil at the beginning of the second day of measurements, black – to the end of the second day (colors are the same as in Figure 4). Solid lines correspond to the shear wave velocity profile, dotted ones – to the longitudinal wave velocity profile.

4 CONCLUSIONS

Let us sum up. The proposed development of the SASW method allows reconstructing not only the shear wave velocity profile but the profile of Poisson's ratio, which is associated with the nature of structure of bonds between grains in granular medium. The experiment conducted points to the possibility of practical realization of remote monitoring of the degree of saturation with fluid of the natural porous media.

The results of this study may be useful in conducting surveys for construction as well as in monitoring the environment when predicting undesirable geodynamic phenomena associated with the loss of stability (landslides, avalanches, etc.). The diagnostics of the degree of saturation is of obvious interest in location of pipeline leaks and in assessment of the degree of environmental contamination. Methods being employed in this study are universal and the results can be applied not only in geophysics but also in other technical applications where the surface waves are used, for example, in the analysis of quality of treatment of machinery parts.

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