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Engineering-ecological research of the upper part of geological section using seismic data

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The paper presents the results of reprocessing seismic data typically lost during hydrocarbon exploration. These data are used to map the velocity properties (longitudinal wave velocities) of the upper part of the geological section, to reduce costly engineering and survey work for industrial and civil construction, and to promote the successful development of precise agriculture in oil and gas regions. Additionally, the study addresses the average shear-wave velocity in the top 30 m of the Earth's surface (V_S^{30}) for seismic risk assessments and to solve engineering-hydrogeological challenges.

Key words: upper part of the geological section, undergroundwater depth, seismic exploration, longitudinal wave velocity.

Introduction. Typically, large-scale industrial development of an area is preceded by geological exploration, in which seismic surveying plays a key role in oil- and gas-producing regions. Geophysicists need to study the velocity inhomogeneities of the upper part of the geological section (UPGS) to eliminate their distorting effects in order to process seismic data. In seismic exploration, the UPGS is the uppermost layer of the geological section. Here, rocks' physical properties (velocity and density) vary most significantly. The section's thickness can range from a few dozen meters (in mid-latitude and southern regions) to several hundred meters (in the permafrost layers of northern areas or where near-surface trap intrusions or salt domes occur). Significant operational resources are expended to acquire data on the structure and model the UPGS, which typically remains unused. At best, the UPGS information is employed as an auxiliary mapping or exploration indicator. For example, geophysical surveys for oil and gas have been made more successful by incorporating nontraditional UPGS investigation methods — such as microseismic logging of shallow wells (down to 50 m) [Tiapkin et al., 2016] — into the main survey program (alongside standard techniques like seismic and electrical prospecting, and supplemental ones like gravity and magnetic surveys). At the same time, the construction of industrial facilities and infrastructure for producing fields requires engineering-geological investigations. Their primary objective is to ensure the stability and integrity of project-

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ed structures under long-term operational loads without dangerous deformations. This requirement must be met throughout the entire structurally distinct portion of the Earth's crust within the zone of potential engineering impact (in exploration geophysics, the UPGS). To assess the suitability of specific UPGS rock masses for construction and forecast environmental consequences, comprehensive engineering-geological studies are needed to characterize the site's structural-tectonic conditions and quantitatively evaluate the rocks' deformations, strength, and filtration properties. However, such studies are typically discrete, allowing for examining rock masses only at certain points and to a limited depth. Meanwhile, a UPGS model obtained during geological exploration (specifically seismic exploration), supplemented and refined with minimal research, can serve as a reliable foundation for planning subsequent engineering and construction work. This approach significantly reduces the scope of expensive engineering surveys while substantially increasing their robustness [Tyapkin, Onyshchenko, 2014].

Results. A highly accurate method has been employed to determine the velocity characteristics of the UPGS down to depths of several hundred meters for any observation system and any wave excitation technique, requiring no additional specialized studies. This method is based on using estimates of average velocity. Within the UPGS, there is a low-velocity near-surface layer and a higher-velocity lower layer (down to depth h_1+h_2', see Fig. 1). The average velocity is evaluated from first-arrival times recorded along equidistant observation profiles at offsets comparable to the thickness of the UPGS. The approach uses the first-arrival times regardless of the wave types (refracted, reflected, head waves, etc.) and is unaffected by the curvature of the UPGS boundaries. It is implemented within the SPS-PC processing system on a PC. The estimates obtained at geophysical observation points are interpolated onto a regular grid across the study area. The main computational parameters of the method are the coefficient k, determined through the ratio of velocities V_1 and V_2, and the offset X_p where first-arrival times are recorded. The proposed approach is not very sensitive to variations in UPGS parameters. To assess the accuracy of the obtained results, one can use the procedures for determining static corrections while processing seismic data. For instance, if at a certain point on the profile h_1=5 m, V_1=700 m/s, h_2=30 m, and V_2=100 m/s, then k=3.02 and X_p=105 m. The computed k can be employed to calculate X_p at other points along the profile over a broad range where V_1 and V_2 were not determined because to attain a 2 ms accuracy in static corrections, the velocities V_1 and V_2 may vary along the profile ≤39 % and ≤27 %, respectively, relative to the velocities at the initial point where the parameters were specified.

Fig. 2 provides an example of using the method to determine the velocity characteristics of the UPGS along a particular (2D) profile, comparing it with the conventional approach of investigating this portion of the geological section via microseismic logging and the refracted-wave method. In this case, incorrect results due to errors in the microseismic-logging data affected the time section. By contrast, the time section with static corrections applied using the proposed approach appears more coherent and is more accurate.

In the example of the northern part of Western Siberia, the construction of a 1:200,000-scale map of longitudinal (P-wave) velocities in the UPGS is illustrated over an area of about 37.5 thousand km^2 [Tyapkin, Onyshchenko, 2014]. This map clearly shows areas of thicker permafrost (with higher velocity values) and lower-velocity areas where permafrost is practically absent («thawed» zones). These «thawed» zones tend to be located along rivers, which meander significantly in the swampy tundra environment of northern Western Siberia. Some of these zones occupy sizeable territories with river-controlled boundaries, indicating a separation of the Earth's crust into tectonic blocks.

This opens additional opportunities for mapping the fault-block tectonics and assessing the associated oil and gas potential

[Tyapkin, 1998]. The resulting *P*-wave velocity map of the UPGS, along with the possibility of converting UPGS *P*-wave velocity into density and engineering parameters, makes it possible to substantially reduce the amount of expensive engineering survey work while significantly increasing its reliability, accuracy, and completeness, as well as facilitating the organization of a comprehensive geoecological monitoring system.

Another promising area for applying the constructed *P*-wave velocity maps of the UPGS is agriculture in steppe and forest-steppe regions, especially precision farming [Onyshchenko, Tyapkin, 2015]. With the help of these maps, it becomes possible to investigate and forecast changes in UPGS moisture content (by area and depth). To this end, the method employs estimated average velocity values in the UPGS derived from first-arrival times at various fixed offsets. This approach allows one to examine the structural features of the UPGS at specific depths (down to those depths). A combined analysis of the relevant UPGS *P*-wave velocity maps makes it possible to determine and predict the three-dimensional moisture content distribution within this subsurface section. It also identifies the sources of its spatial variations (whether natural (including structural-tectonic) or anthropogenic) to inform management decisions in water-resource and agricultural activities. In the past, these studies were conducted by the authors in Russia. There are now positive results of applying such technologies in Ukraine as well, based on seismic exploration data from LLC «Georozvidka».

The average shear-wave velocity in the top 30 m of the Earth's surface (V_S^{30}) is one of the key parameters in geophysical engineering-environmental research, thanks to its significance and wide range of applications. It plays a crucial role in classifying UPGS based on their seismic characteristics, which is essential for seismic risk assessment and earthquake impact modeling, particularly in Ukraine [Dovbnich, Viktosenko, 2023; Tiapkin et al., 2024]. Eurocode-8 [CEN, 2004], adopted in EU countries, has V_S^{30} as the principal characteristic to determine the seismic UPGS class. Beyond its primary role in seismic analysis, V_S^{30} is also employed as an indirect indicator for evaluating geotechnical parameters such as bearing capacity, density, and lithotype. Rock moisture is a major factor affecting V_S^{30}. Hence, there is a possibility of predicting underground water depth (where direct hydrogeological measurements are not available — down to 30 meters) using V_S^{30} data, including via machine-learning methods.

This can be illustrated by the example of Texas (USA). There, high-resolution open datasets for V_S^{30}, undergroundwater levels, and lithology are available [Li et al., 2020; Jasechko, 2023]. They enable comprehensive analysis, machine-learning model testing, and the assessment of physical relationships under real-world conditions. The V_S^{30} dataset was reprojected into EPSG:4326 to ensure consistency with other data. Data were collocated using the *cKDTree* algorithm, which matched each underground water-level measurement to the nearest V_S^{30} point within 0.05° (~5.5 km). Three machine-learning models were used to predict underground water depth: simple regression, Random Forest, and Extra Trees. The simple model served as a baseline, but its assumption of linearity is often insufficient for complex geological and geophysical relationships. Random Forest constructs multiple trees and averages their predictions, making it robust to noise, outliers, and nonlinearities. Extra Trees, a

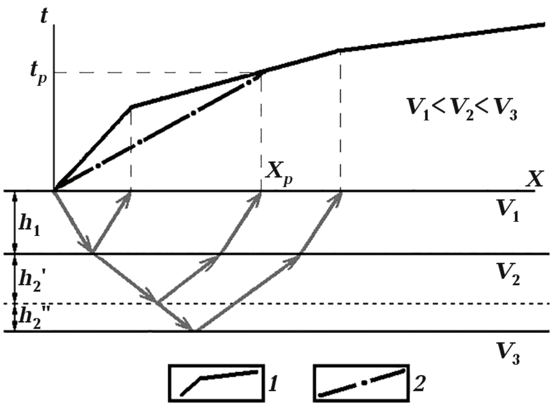

Fig. 1. Refraction travel-time curves of the first wave arrival from the model section (*1*) and conditional layer (*2*).

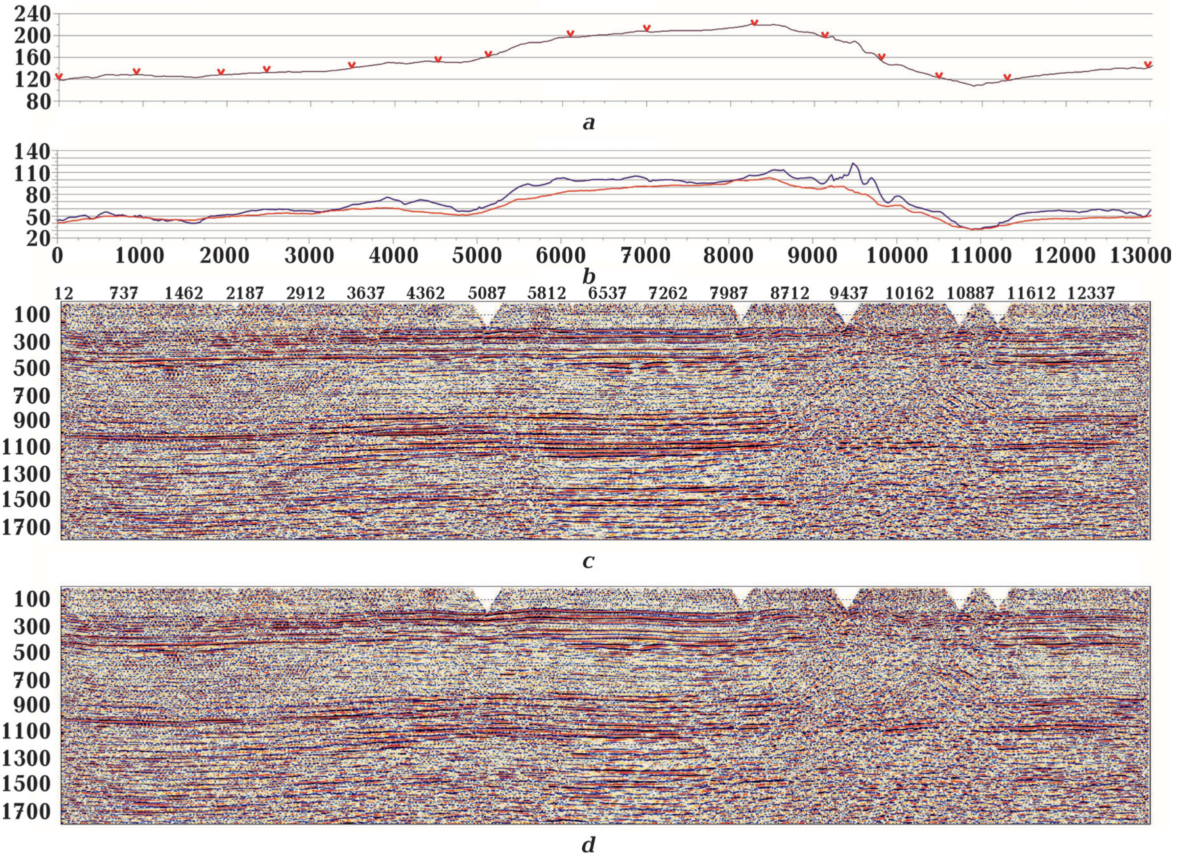

Fig. 2. Example of using the proposed method for determining UPGS velocity characteristics in the procedure for deriving static corrections when processing seismic data along a specific (2D) profile, compared with the traditional approach to studying this part of the geological section using microseismic logging and the refracted-wave method in the Buzuluk area (southeastern East European Platform): *a* — the relief profile (2D) plot indicating points/positions where microseismic logging was carried out, m; *b* — plots of static corrections obtained from microseismic data (blue) and from the proposed UPGS velocity-determination method (red), microseconds; *c* — the 2D time seismic section for the profile using static corrections derived from the proposed UPGS velocity-determination method; *d* — the 2D time seismic section for the profile using static corrections based on microseismic data.

Random Forest variant that adds randomness in node splitting, was tested for potential performance gains. The model evaluation used R^2 and RMSE parameters. The simple regression showed an R^2 of 0.002, indicating no direct V_S^{30} — undergroundwater correlation. In contrast, Random Forest achieved an R^2 of 0.728 and an RMSE of 4.417 m, demonstrating a high predictive capability. Extra Trees also incorporated different geological (lithological) conditions and performed slightly better (R^2=0.733, RMSE=4.255 m). Thus, adding geological (particularly lithological) data to the models leads to only a small improvement in predictive accuracy (an increase in the determination coefficient R^2 by roughly 2—3 %). This may indicate that V_S^{30} already captures a substantial portion of the information governed by the geological (lithological) and geotechnical conditions of the UPGS. However, the future use of more detailed 3D geological models and/or high-resolution classifications of soil types could yield a more substantial enhancement in predictive outcomes.

These findings can serve as a basis for developing automated workflows that utilize V_S^{30} for initial underground water assessments. Future research may include validating these models in other geological-geophysical settings, integrating more geotechnical/hydrological data, and exploring other machine learning algorithms (such as support vector machines or neural networks) to enhance accuracy.

Conclusions. In the progress of processing seismic exploration data for studying deep geological structures and searching for mineral deposits, geophysicists need to address the issue of velocity heterogeneity in the UPGS to eliminate its distorting influence. Substantial operational resources are spent acquiring data on the structure and developing a UPGS model, which typically remains unused afterward. However, a *P*-wave velocity map of the UPGS, supplemented by minimal specialized survey work, can serve as a foundation for designing engineering and construction projects in the study area. If a strong correlation is established between rock density and *P*-wave velocity, the latter can be converted into density and engineering parameters. This approach significantly reduces the scope of additional, expensive engineering investigation while substantially increasing its reliability.

Another promising direction to utilize the constructed *P*-wave velocity maps of the UPGS lies in agriculture across the steppe and forest-steppe regions, especially in precision farming. These maps enable comprehensive analysis and forecasting of moisture variations in the UPGS and the identification of natural (including structural and tectonic) or anthropogenic sources of those variations in this portion of the geological section. Such insights support informed decision-making in water management and agricultural planning and operations.

The results demonstrate the potential for using V_S^{30} as a proxy parameter to predict underground water depth (up to 30 m) using machine learning models. The results indicate that ensemble methods such as Random Forest and Extra Trees Regress or effectively capture the nonlinear relationships between shear-wave velocity and groundwater levels (with determination coefficients R^2 reaching about ~0.72—0.73 and a root-mean-square error of roughly — ~4.2—4.4). At the same time, adding geological (particularly lithological) data yields only a small improvement in predictive accuracy (an increase in R^2 of about ~2—3 %). Despite these overall promising outcomes, the research emphasizes the need to validate the models in other geological and geophysical settings to ensure their possibility of generalization, as well as the importance of considering potential limitations related to data resolution and spatial variability.

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Інженерно-екологічні дослідження верхньої частини геологічного розрізу за сейсмічними даними

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Показано результати переобробки сейсмічної інформації, що втрачається в процесі пошуків вуглеводнів, для картування швидкісної характеристики (швидкості поширення поздовжніх хвиль) верхньої частини геологічного розрізу для скорочення дорогих інженерно-пошукових робіт для промислового та цивільного будівництва та успішного розвитку точного землеробства на території нафтогазових регіонів, а також середньої швидкості поширення зсувної хвилі у верхніх 30 м від земної поверхні (V_S^{30}) для оцінювання сейсмічних ризиків і вирішення інженерно-гідрогеологічних завдань.

Ключові слова: верхня частина геологічного розрізу, глибина залягання підземних вод, сейсморозвідка, швидкість поширення поздовжніх хвиль.