The study undertakes to solve the problem of obtaining reliable seismic data in swampy areas. Raw hydrocarbon deposits in the North of Perm Krai are a promising asset, but their geological survey is constrained due to problematic surface conditions. Seismic exploration is the most detailed and reliable remote method of geological subsurface studies, but any state-of-the-art seismic 3D survey requires covering a much larger surface area than an actual area of a targeted subsurface survey. Swamps tend to strongly attenuate seismic waves, thus complicate a further geological interpretation of obtained data, and significantly limit the choice of engineering tools and techniques of surveying. Also it is impossible to avoid the influence of hard surface conditions in territories extending over hundreds of square kilometers. In order to explore the possibility of obtaining high-quality data in such conditions, we offer a comprehensive pilot survey using various recording and seismic wave excitation facilities. We analyzed and explored the possibility of solving this problem by using advanced seismic exploration methods. The study looks into the technology of obtaining primary data and into the stage of information processing for its further geological interpretation. This is the first time that Geoton seismic pulse source and GS-ONE high-sensitivity seismic receivers have been used for these purposes. According to the findings, there is an obvious advantage of using the blast over pulse source, especially in the swamp bed itself. At the same time, Geoton proved to be highly eco-friendly and safe, which makes it possible to use it in seismic exploration works of inhabited areas. The results of processing the pilot survey data show that the single seismic receivers produce wave patterns with the best quality and accuracy. The paper offers the seismic exploration techniques in swampy conditions and in territories that have increased requirements to environmental protection and safety.
**Introduction**

Obtaining reliable seismic data in seismically restrained swampy areas is somewhat problematic. Behavior of deformation waves in inhomogeneous media has always been in the focus of studies of geophysics, geologists and even builders [1, 2]. Their interest is associated with the fact that the anomalies caused by the influence of these media can have a substantial effect on the wave pattern in the target survey intervals. Now specialists note that the survey focus lies in small-size and low-amplitude targets, while the confounding factor of near-surface section (NSS) anomalies can change or completely hide such a target [3].

Apparently, multiple methods for factoring in the NSS anomalies exist and are actively used [4–8]. However, according to the author’s personal findings accumulated over the past 10 years of work with the seismic exploration data in various Russian territories, some of the anomalies can be so powerful that it appears to be impossible to factor them at the processing stage. Therefore, it is advisable to minimize them at the stage of obtaining primary data, i.e. during field seismic exploration works [9].

The problem of concern is highly relevant for the territory of Perm Krai, since the main bulk of seismic exploration works is performed using compact drilling rigs that are incapable of drilling blast wells deeper than 10 m, which excludes the influence of a swampy bed on a seismic signal generation. Apart from the signal attenuation, suboptimal conditions of excitations produce intense waves, i.e. noise events, where Rayleigh waves and ringing pulses [10] are the most impactful. It is not possible to use more powerful machinery, as it violates the regionally adopted environmental protection standards [11], which forbid cutting down trees.

**Materials, Research Methods and Analysis of Results**

In order to analyze the possibility of improving the quality of the material obtained in the restrained surface and geological conditions, a pilot survey was made in Privolzhsky Federal Okrug, in the territory of Krasnovishersk District, the Northern part of Perm Krai. The 2D common depth point method profile entered the swamp (adverse surface conditions), forested area and the river Vilva flood plain. Such a diversity of surface conditions enabled obtaining the necessary wide range of data for the analysis.

The surveyed site is located in a zone highly unfavorable for seismic and geological works, characterized by pronounced wave field distortions, seismic energy absorption and dissipation, and high level of intense noise waves [12]. The effectiveness of the seismic exploration works deteriorates due to an over three-meter-thick peat bed covering the ground surface (which dampens seismic energy and causes reoccurring low-frequency vibrations), argillaceous-marl bed and Solikamsk horizon limestones. Such mechanical characteristics greatly influence generation of elastic waves [13]. Fig. 1 shows NSS velocity-depth model with lithology columns, demonstrating the surface and subsurface conditions of the test profile’s location. The near-surface section throughout the profile is expressly inhomogeneous; the selected area has widely diverse surface and subsurface conditions, which corresponds to the objectives of the pilot production works.

![NSS velocity-depth model](image-url)
These works offer a practical value due to the fact that hard-to-reach areas are seldom included in the scope of seismic exploration works, whereas the wells that are drilled in them hardly ever undergo geophysical surveys. In these conditions, unreliable seismic data can deteriorate reliability of recommendations for a well laying [14], which entails significant financial risks.

Seismic signal recording was conducted via two receiver lines, using groups of twelve GS-20 DX geophones on the one line and GS-ONE single seismic receivers on the other. The receiver lines were unreeled alongside one another in identical surface conditions. Regardless of the type of surface conditions, the seismic dataset obtained using GS-ONE seismic receivers has certain differences from the data obtained using GS-20 DX geophones. In the first case, the wave pattern contains a wider spectrum of registered frequencies but with smaller amplitudes (Fig. 2) and is confounded by noise influences, which are especially obvious in the microseism area (Fig. 3, a). Wind is the main noise event, which is quite difficult to exclude during the recording, but it can be suppressed during processing by powerful tools designed for this purpose [15, 16]. Excessive levels of noise are caused by a higher sensitivity of GS-ONE single seismic receivers, amounting to 78.7 (V/m/s) against 19.7 (V/m/s) of one GS-20DX device [17]. A higher level of amplitudes in using a group of geophones (Fig. 3, b) is achieved through the group statistic effect [18, 19]. The attenuation effect of the surface-type noise waves through grouping was not fully achieved in these conditions. Probably, the geophone group (being an interference system) failed to provide a sufficient degree of the intense noise wave suppression due to the NSS complex structure, fluctuations of kinematic and dynamic parameters of useful waves and noise effects.

Another reason of this failure was that the noise wave suppression technology was designed as a system customizable to the individual elastic wave fields that vary across regions [20, 21, 22]. Grouping seismic receivers with constant parameters not only reduce the noise wave suppression capability, but also distort them upon recording, which is counterintuitive, taking into account the existing methods for surface waves’ interpretation [23].

Notably, the use of single seismic receivers makes reeling and unreeling of the field equipment significantly easier, as the weight and size of GS-ONE receivers is much less (about 0.2 kg vs. almost 2.0 kg weight of GS-20 DX), which enables a more effective use of the seismic crew personnel, thus, improves the overall performance and reduces the costs of the field operations [24].

At the stage of the seismic data processing, time sections obtained using the single seismic receivers will be taken into account. However, further analysis of the primary seismic data will only be based on the materials obtained using GS-20 DX geophones, since the wave pattern they produce is more expressive and visually representative.
The seismic signal excitation in the test profile was achieved using a traditional method with shallow drilling (down to 10 m) and the technology for blast charge laying below the base of the low-velocity layer (LVL) at the depth of 20 and 30 m. Besides, Geoton-15 compact pulse source was used as the vibration excitation source. The device belongs to the new generation of pulse sources and meets the requirements of environmentally safe operations.

In the southern, dry-land part of the profile, sand-and-gravel deposits occur at the depth below 25 m. These conditions adversely impact the seismic signal excitation, which affects the wave pattern obtained when the blast charge was placed at a depth of 30 m. Compared to the seismogram registered with the 20-m charge depth, it has lower amplitude-frequency characteristics. The difference between the records from the depths of 20 m and 8 m is minimal. The seismogram obtained from the eight-meter well has a more pronounced sound wave train, which has somewhat narrowed the frequency spectrum, but can be easily excluded at the stage of the seismic data processing.

Fig. 4 (I) shows the amplitude-frequency characteristics of the seismic records obtained during the works in the dry land part of the profile, where it is clear how quickly the seismic signal attenuates when excited from the depth of 30 m.

In the central, swampy part of the profile, the record obtained from the signal excitation at the depth of 30 m shows an apparent continued impact of sandy deposits on the amplitude-frequency characteristics of the signal (Fig. 4, II a), albeit less than in the forested part. The records obtained from the depths of 20 m and 8 m differ by frequency: the eight-meter record has a narrower spectrum, associated with the influence of low-frequency noise waves, which intensity grows as the blast charge laying depth decreases.

The data shown in Fig. 4 (II, b, c) make it possible to trace the impact of the low-frequency constituent of the record on the general wave pattern; the spectrum becomes narrower.

Based on the assessment of the primary seismic data, a conclusion was made that blast charge positioning below the LVL base is not always justified: seismic signal generation depends to a larger extent on the immediate lithological conditions of the charge placement than on the depth of its embedding.

In order to obtain reliable high quality field data in the conditions of swampy areas, it is necessary to know exactly the depth of the swamp’s bottom, since it is crucial to place the charge in a dense rock. Apart from establishing favorable conditions for seismic signal excitation, the opportunity to observe these parameters will help to avoid the risk of the charge surfacing, which is against the safety rules of blasting operations [25].

The described situation suggests a high degree of NSS lateral inhomogeneity, posing yet another challenge to the seismic exploration, i.e. a detailed forecast of NSS lithological composition in order to determine the optimum charge laying depth. The microseismic logging is a sufficiently reliable method for the necessary forecast, but it proves to be cost ineffective at high well spacing density. As a rule, a network with a density of 1 well per 1 km² is used, which does not provide a detailed picture of NSS lateral variability.

It has recently become popular to combine seismic exploration works with geoelectric surveying. We believe one of these methods to be quite promising. In particular, it is the continuous

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**Fig. 4. Amplitude-frequency curves of records obtained by blasting:** I) on land in a well with the depth of 30 m (a), 20 m (b) and 8 m (c); II) in a swamp in a well with the depth of 30 m (a), 20 m (b) and 8 m (c)
electromagnetic scanning (EMS) of the section using the method of time-domain electromagnetics and georadar profiling (GRP) [26, 27]. The results obtained by this technology confirm feasibility and effectiveness of the method for NSS study.

The seismic vibration pulse source Geoton-15 represents an alternative means of exploration in swampy areas. It is compact, low-weight, deforms the surface insignificantly during use and is convenient for transportation in groups or individually. These features make it a good option for exclusive zones such as various types of water areas, environmentally restricted areas, inhabited areas, or industrial areas. Notably, PJSC Permneftegeofizika specialists developed an effective system aimed at conducting the seismic exploration works in water areas and bottom drilling from ice during winter seasons [28]. However, the authors of this method confirm that this technology is unfeasible in channel parts of the water areas with a layer over 10 m.

The Geoton source can be used in almost any territory [30]. Slavneft-NPC LLC has demonstrated a unique example of its use for seismic signal excitation during seismic exploration works using the 3D common depth point method in the East Lokosovskoe field area in extremely complicated surface conditions, including the main channel and flood plain of the river Ob. The use of pulse sources resulted in minimizing irregularities of the employed acquisition systems.

In ice cover areas, the Geoton sources were successfully used [31]. It is notable that a group of sources towed by an all-terrain vehicle still has certain limitations as to the minimum ice thickness, since its weight reaches 10 tons. This is much less than the large sources like Yenisey [32], but quite a lot during warm winters that are more often now. From time to time researchers discuss the possibility of creating even lighter sources, however, a pulse that would be sufficient to ensure the exploration depth exceeding 1 km, has to be produced by a source having a respectively large weight [33–36].

In the course of the aforementioned works, the Geoton source has been used in Perm Krai for the first time. The wave pattern registered during the dry-land part of the exploration area appeared to be quite different from the acquisitions in the swamps. In the dry land, the obtained data were comparable to the blast data, first events were clear, fragments of the reflected waves were visible in the primary material (Fig. 5, a). The record registered in the swampy conditions was distorted by powerful low-frequency noise waves associated with the unstable icy bed of the swamp surface and caused by the surface swaying effect during the source operation (Fig. 5, b).

However, seismic exploration is a complex and staged process where the primary data obtaining is just the first step. A.V. Cherepovsky, a well-known Russian scholar working in seismic exploration studies, stated in his book, "many geophysicists still stick to the old belief that if there is no (visible) signal in the initial data, it will not appear in the final sections. The time has come to call this idea in question."

A priori time sections (after summation but before processing) obtained using a blast source located below the LVL base have the best quality of summation; reflections correlate practically throughout the entire recording interval.

A priori sections obtained using the blast source from the depth of 8 m show a great impact of the noise waves (especially in the swampy part of the profile).

The lowest summation quality and almost a complete lack of the reflections in the target intervals were obtained in the time sections with the pulse source (Fig. 6, c).
As mentioned earlier, it would be counterintuitive to make conclusions about the quality of seismic data without considering material processing results. The processing is intended for extraction of useful information from the field seismic data. The seismic data processing is mostly based on solving inverse problems. An inverse problem in seismic exploration deals with determining the structure of the seismogeological environment from the acquisitions of the elastic wave field occurring in it [38, 39].

A poor quality of a priori summation is related to the influence of the surface noise waves that typically have low frequencies and large amplitudes. At the final processing stage, time sections for all the excitation sources have demonstrated the quality acceptable for a further interpretation. It is clear that achievement of such a result requires a detailed control of processing [40, 41].

According to the processed results, the best-quality material in terms of wave field characteristics (higher coherence and record resolution in time sections) was in case of using the blast excitation sources. Sections are mostly comparable for the charge laying depths of 8 meters and 20 meters (Fig. 7).

The time section with the pulse source of excitation showed a lower performance against the blast source having produced a narrower frequency spectrum and accuracy (Fig. 8); therefore, it may be limited in terms of the capability of a small target interpretation [42]. Nevertheless, owing to its technical features, simplicity and safety of the operation, the Geoton pulse source represents an attractive alternative source of the seismic signal excitation.

The present study and negotiations with the source manufacturer revealed certain details that may result in
Fig. 8. Frequency spectra of time sections obtained by signal excitation using the pulse (a) and blast (b) source

Fig. 9. Time sections built on the data obtained using GS-20 DX geophones (a) and GS-ONE single seismic receivers (b) low-amplitude faults (Fig. 9). Notably, for single receivers placed with the sufficient density (at an interval of 10–12 m), the laboratory grouping is available, referred to as effective by many researchers [43–45] improving the frequency spectrum of the generated elastic waves, thereby increasing the level of the wave pattern accuracy.

As for the grouping impact of the seismic receivers and single geophones on the wave pattern, it has been discovered that in the context of these works, there is only a small difference in the accuracy of the reflecting horizons tracing. The single receivers tend to produce a more detailed picture of small-sized targets and low-amplitude faults (Fig. 9). Notably, for single receivers placed with the sufficient density (at an interval of 10–12 m), the laboratory grouping is available, referred to as effective by many researchers [43–45].

**Conclusion**

1. Time sections obtained using different excitation sources have nearly 100 % traceability of the target reflections followed by processing, but the blast sources perform better in terms of detail and resolution.

2. After the entire set of the data processing operations, the sections with the blast excitation source in the wells with the depth of 8 meters and 20 meters showed an equal quality of the target reflections. Therefore, it appears to be counterintuitive to drill deeper wells that require much more funds and efforts. Special attention should be paid to analyzing the NSS lithological features when selecting the blast charge laying depth.

3. It is advisable to conduct a preliminary study of the NSS structure using methods alternative to the seismic exploration, e.g. EMS and GRP showed promising results. The detailed picture of the NSS lithological structure will help to avoid the charge placement in adverse conditions and exclude an excessively deep laying.

4. The pulse sources produce time sections with a lower resolution and detail. Nevertheless, if we consider the seisnomogeological area complexity, lack of their field use experience and novelty of such materials for processing, we believe that such sources might be helpful, especially in the works conducted in the zones highly sensitive in terms of environmental protection and safety.

5. The single seismic receivers have demonstrated a final result comparable to that obtained using the groups of geophones. The former have an advantage of producing more detailed time sections, whereas the undoubted convenience and lightweight of the field equipment reduce the unreeling efforts.

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