

Frequency components of radargrams in analyses of shallow soil cavities

Daniliev S.M *, Danilieva N. A

Saint Petersburg Mining University

Abstract

The urgency of the issue being studied is determined by widespread large-scale implementation of ground penetrating radar (GPR) method within the study practice of technical state of various engineering-geological sites over a long operational period. Such buildings and structures as dams, architectural landmarks, residential and industrial buildings, temples and churches, roadways and takeoff runways may be referred to main engineering and geological sites which have been studied via ground penetrating radar method. Cracks of different length, orientation and opening, as well as cavities of various localization, being distinguished by filling material, are the main types of irregularities in the above-mentioned sites, which were being formed in the process of prolonged or improper operation. However, due to vastness of the irregularities being studied and the impossibility to include all the types of possible defects into this article, we have settled on the cavities which are the most commonly encountered in the course of practice only. This article considers the approach to analysis of the electromagnetic wave field frequency characteristics being applied during conducting ground penetrating radar studies of irregularities in the structure of engineering-geological sites on the basis of the results of electromagnetic wave fields mathematical simulation, and of the results obtained in experimental studies at real engineering-geological sites as well. There has been proposed a method based of inverse Fourier transformation for studying spectrum shift in georadargrams. The georadargram is a set of registered signals, which is obtained during even movement of the georadar along the survey line. Due to that, this article is aimed at attraction of analysis of wave electromagnetic field attributes in addition to standard methods of ground penetrating radar (GPR) data processing and interpretation, which allows to extend significantly prospect capabilities of GPR method by obtaining extra data on heterogeneous zones parameters at engineering and geological sites, and, thus, proceed from qualitative notions on technical condition of studied object to quantitative ones.

Keywords: Ground Penetrating Radar (GPR); Frequency Shift; Energy Spectrum; Fourier Transformation; Georadargram; Period gram.

1. Introduction

The ground penetrating radar (GPR) method, which has distinct advantages due to its high resolution and operational efficiency at field work performance, gains active popularity in the current practice of evaluating the technical condition of engineering and geological sites, and the most important thing is that this method does not require the deformation of the site being studied and interference thereinto. As the result of continuous operational and vibrational loads of engineering and geological processes, for example, suffusion, weathering, cavities of various length, direction and width, and cavities of various localization, distinguishing by filling material, are the most commonly encountered type of engineering and geological sites [1]. Cavities of various engineering sites are distinguishing by the shape, dimensions and filler material. In the most cases, as a result of underwashing processes, cavities are formed in the area of strengthening structures adhesion of geotechnical sites with geological environment, such as under the reinforced concrete slabs in the area of contact with the dam soil foundation, within the holdfast space at the contact of supports and rock, at the contact of pavement layers, etc. [2]. Thus, the cavities roof forming depth is less than 1 m for this class of problems in the most cases. The analysis of kinematic characteristics features of the electromagnetic wave field makes it possible to quickly localize the zones of cavities development. However, the practical needs meet the fact that it is not enough to detect potentially dangerous areas of

cavities development only, but also it is required to evaluate the cavity filler material which is worth to achieve by the introducing of the wave electromagnetic field dynamic analysis only. Therefore, in order to introduce the dynamic analysis of the electromagnetic field characteristics into practical application, there is a need to create theoretical bases utilizing the results of mathematical simulation and experimental studies of cavities with known properties [3-5]. STATISTICA software was used for solving the problem of transition to the dynamic attributes of wave field frequency. The transition from the amplitudes to the frequency itself is possible using the inverse Fourier transformations.

Fourier Transformation is an integral transformation that expands the initial function in the basic functions, and the sinusoidal functions (or imaginary exponents) serve as the above-mentioned ones, i.e., it represents the initial function as an integral of sinusoids (imaginary exponentials) of different frequency, amplitude and phase. Transformation is reversible, wherein the inverse transformation has virtually the same form as the forward transformation.

The Fourier transformation mathematical sense consists in the representation of the $y(x)$ signal as an infinite sum of sinusoids of the $F(\omega) \cdot \sin(\omega x)$ form. The $F(\omega)$ function is called the Fourier transformation either Fourier integral or Fourier signal spectrum. The inverse Fourier transformation modifies the $F(\omega)$ spectrum into the original signal $y(x)$. One of the simplest forms of vibrational displacements is a sinusoid to be described by the equation of the following form:

$$y = F(t) = A \cos \omega t + B \sin \omega t = a \sin(\omega t + \varphi),$$

Where a is the amplitude of vibration and φ is the phase.
The coefficients A and B can be determined using these values:

$$A = a \sin \varphi; B = a \cos \varphi$$

This sinusoidal waveform is monochromatic with regard to ω frequency. It has a single amplitude value a as well as the phase φ in the frequency function. If represent graphically this function having plotted the frequency along the X-axis and the amplitude (or the phase) along the Y-axis then, a single straight-line segment corresponding to natural oscillation frequency ω_0 will be obtained. This will be the simplest amplitude (or phase) $y=F(x)$ function spectrum, consisting of a single spectral line in this particular case.

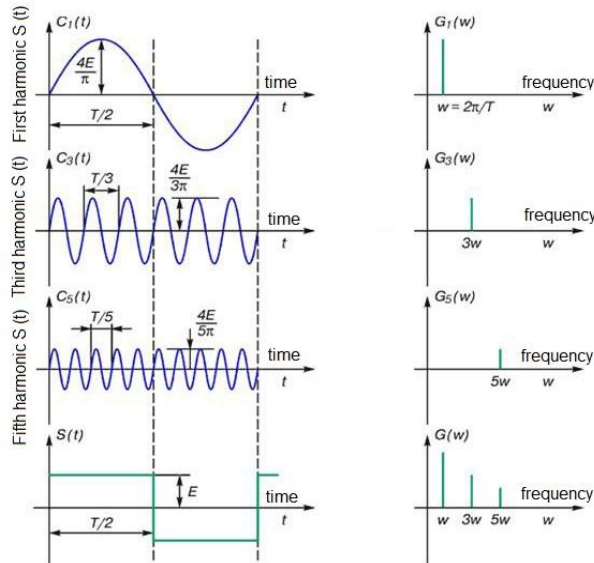


Fig. 1: Presentation of a Rectangular Pulse via the Sum of Harmonic Components

When adding several sinusoidal oscillations with the various frequencies $\omega_1, \omega_2, \dots, \omega_n$, an amplitude spectrum of total oscillation is characterized by the presence of n lines, i.e., this spectrum will be a linear one. In this case, the function representing the mode of oscillations is expressed via the sum:

$$F(\omega) = \sum_{\omega=\omega_i}^{\omega_n} [A(\omega) \cos \omega t + B(\omega) \sin \omega t]$$

If the vibrations are of non-periodic nature, then the $F(t)$ function can be represented as the limit of the sum of an infinitely great number of harmonic oscillations that differ in frequency by an infinitesimal value $d\omega$, i.e. use the Fourier integral:

$$F(t) = \frac{1}{\pi} \int_1^{\infty} [A(\omega) \cos \omega t + B(\omega) \sin \omega t] d\omega$$

Where

$$A_0 = \int_{-\infty}^{\infty} f(t) dt; A(\omega) = \int_{-\infty}^{\infty} f(t) \cos \omega t dt; B(\omega) = \int_{-\infty}^{\infty} f(t) \sin \omega t dt$$

(Boganik and Gurvich 2006).

2. Subject of research

Studies of various sizes cavities and filler material were carried out at Votkinsk Hydroelectric Station located near Chaykovsky in Perm Krai (ref. to map). Profiles diagram is given in Figure 3.

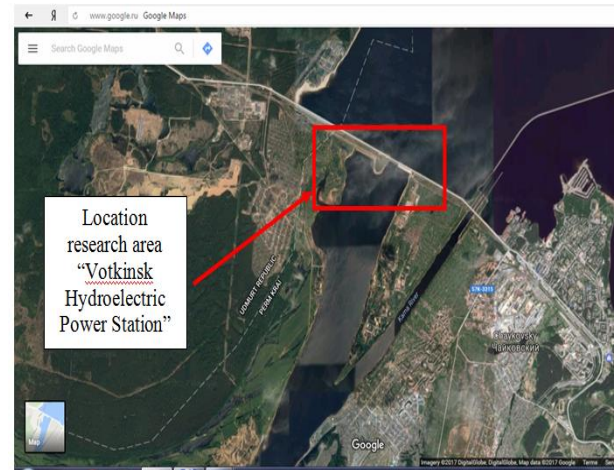


Fig. 2: Overview Map of Studied Area.

[<https://www.google.ru/maps/@56.7795008,6910m/data=!3m1!1e3?hl=en>], 54.0790056,

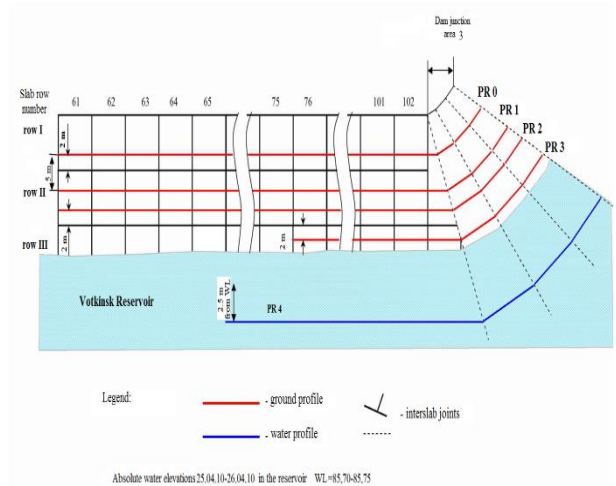


Fig. 3: Diagram of Profiles along Votkinsk Hydro electro Station Side.

Votkinsk Hydroelectric Station is an artificial complex hydraulic structure, located at bottom land on the left bank of the Kama River, and joins the hydraulic power plant building with shipping lock. Dam length is 1319 m. Dam maximum height is 25 m. Dam width at crest is 22.2 m. By its type, the earth fill dam is homogeneous, upstream side protection from waves is performed by reinforced concrete slabs placed on modern alluvial sediments of Quaternary age (Q4-al).

To study the structure of wave electromagnetic field of hydraulic structures cavities, it is necessary to carry out theoretical research based on mathematical simulation, as well as physical simulation, confirming theoretical researches results.

3. Mathematical and physical modeling

3.1. Parameterization the models of the cavities by hydro-power plants on the basis which the mathematical modelling

Cavities electrophysical properties (electrical conductivity (σ) and permittivity (ϵ)) are determined by cavity filling material. Such basic materials of the cavity filling as water, air, and modified rock may be distinguished in the engineering facilities, depending on the cavities formation conditions. In order to build basic models describing the features of the wave electromagnetic fields, depending on the cavity electrophysical properties variations, the geometric properties are considered to be the constant ones. The following geometric parameters are selected in order to obtain higher resolution of the electromagnetic wave field: cavity length $\Delta X=1$ m;

$h_2=70$ cm, $h_1=30$ cm, where h_2 and h_1 are depth marks of the cavity base and roof, respectively. These geometrical parameters provide getting reflections from the cavity base with the filling material having the highest propagation velocity of the electromagnetic waves (air) and make it possible to consider the cavity not as a local site, but as a site with a certain length. Geological environment enclosing a cavity, while calculating the basic models, is considered to be isotropic one without additional interference as well as sand-filled ($\epsilon=9$; $\sigma=0.001$ cm/m), because the sand is the most favorable geological environment for local cavities formation.

Four models characterized by a single cavity geometry, host medium and various cavity filling materials (Fig. 4), such as air, water, modified rock (clayish soil), and sandy cobble [6] were synthesized from the cavities electrical properties variations as part of the electromagnetic wave fields features research.

The electromagnetic wave phases analysis arouses greater interest. The central frequency spectrum shift of the probe pulses, depending on the electromagnetic wave passing medium, it is an important feature of the electromagnetic wave fields [7-10].

On the ground of the synthesized basic models analysis (Fig. 5) of the cavities, considering the variations of the cavity electrophysical properties, one may draw conclusions about the integrity and diversity of an electromagnetic wave field. The presence of a wave reflected from the cavity roof on the seismic feature time section, diffracted waves (quasi-hyperbolas) seismic features from the left and right boundary of the cavity are the common effects of the electromagnetic wave field in the above-mentioned models. The seismic feature of the waves reflected from the cavity base is observed in the majority of cases except for the cavity filling clay material due to the reason of strong electromagnetic waves absorption. Manifestation of the electromagnetic waves effects, such as the presence of the multiple diffracted and reflected waves is an extra common feature of the wave field. The manifestation of the electromagnetic waves reverberation effects is an indirect indicator of the water fraction predominance in the medium being studied.

3.2. Mathematical modelling

To perform mathematical simulation of the wave electromagnetic fields, due to similarity of data structure within the wave methods kinematic models, one can also use seismic survey software packages with a high degree of reliability. The ray-path method and the geometrical optics principal laws are applicable in both cases. However, for reliable study of the kinematic and, above all, the dynamic features of electromagnetic wave fields, there is a need to apply special algorithms considering the electrophysical properties of the host medium and the material for cavities filling. Recommendations for the use of GPR investigations in the package of geotechnical works 2000.

The simulation of complex, heterogeneous media, including cavities with such fillers as air, water, pebble and clay matter, is based on a precise calculation scheme which is relied on the finite-difference method.

The simulation via finite difference method makes it possible to consider all the features of emission and propagation of electromagnetic waves in the medium model being studied. Synthesis of the model electromagnetic wave fields is based on the solution of Maxwell's equations within the time domain via the finite-difference method. The components of the fields E , H in each node of the elementary cells being considered represent the calculation result. This makes it possible to visualize the field that it is important for the understanding of the regularities of electromagnetic waves propagation in the medium under study.

The model by which synthetic radargrams were calculated is given in Figure 4 and presents a schematic design of Votkinsk Hydroelectro Station at the upstream part of which a concrete slab is located with a sandbase thereunder wherein a cavity of variable capacity was designed artificially.

As discussed above, the cavities in engineering facilities are formed at a shallow depth, so, to synthesize the cavities basic models, there

is a need to select a central frequency of the probing electromagnetic pulses, which provides a high detail degree of the electromagnetic waves propagation study. The degree of the study detail is determined by the length of the electromagnetic wave in the medium under study and the radius of the first Fresnel zone at a particular central frequency. The less the wavelength and the radius of the first Fresnel zone, the more the detail level of the studies. In Fig. 3, there is plotted the dependence curves of the electromagnetic wave lengths (λ), the radii of the first Fresnel zone (R_f) at a cavity position depth of 30 cm (typical for the dams of hydro-technical utilities and vertical openings), on the central frequency of the probing pulses in the media (f) characterizing the basic filling materials of the cavities. As shown in Fig. 3, to provide cavities researches with maximum level of detail, it is necessary to choose high-frequency antenna systems, but for the media with an attenuation of 1-2 dB/m, the depth of studies for the frequencies above 1,200 MHz is less than 1 m, which fails to meet the depth requirements.

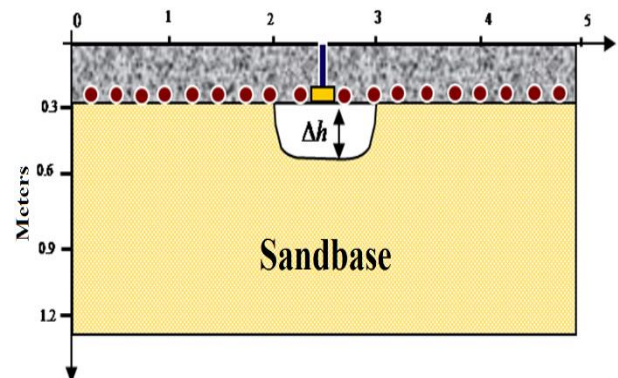


Fig. 4: Model for Mathematic Modeling of Votkinsk Hydro Electro Station Side.

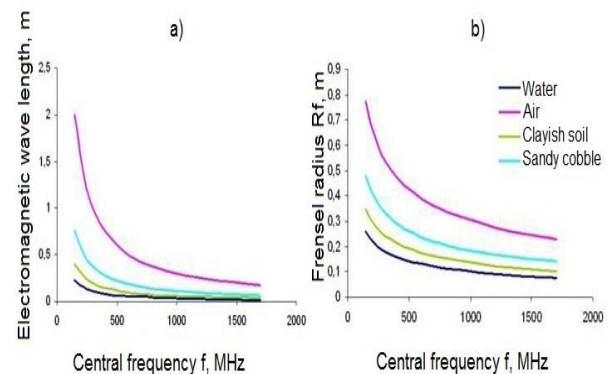


Fig. 5: Dependence Curves of the Electromagnetic Waves Lengths (A) and the Radii of the First Fresnel Zones (B) on the Frequency for Various Cavities Filling Materials.

The frequency equal to 700 MHz provides the required detail and depth of real engineering facilities study and is implemented as a set of different georadars. In view of this, the cavities basic models are designed for this central frequency.

3.3. Kinematic characteristics of the electromagnetic wave fields

Kinematic characteristics of the electromagnetic wave fields can be analyzed for the cavities according to simulation results. The following parameters are referred to the kinematic characteristics:

- Velocity of electromagnetic waves (v [cm/ns]);
- Reflection arrival times of the cavity roof and base waves ($2t$ [ns]);
- Lengths of the electromagnetic waves within the cavity filling material and a host medium (λ [cm]).

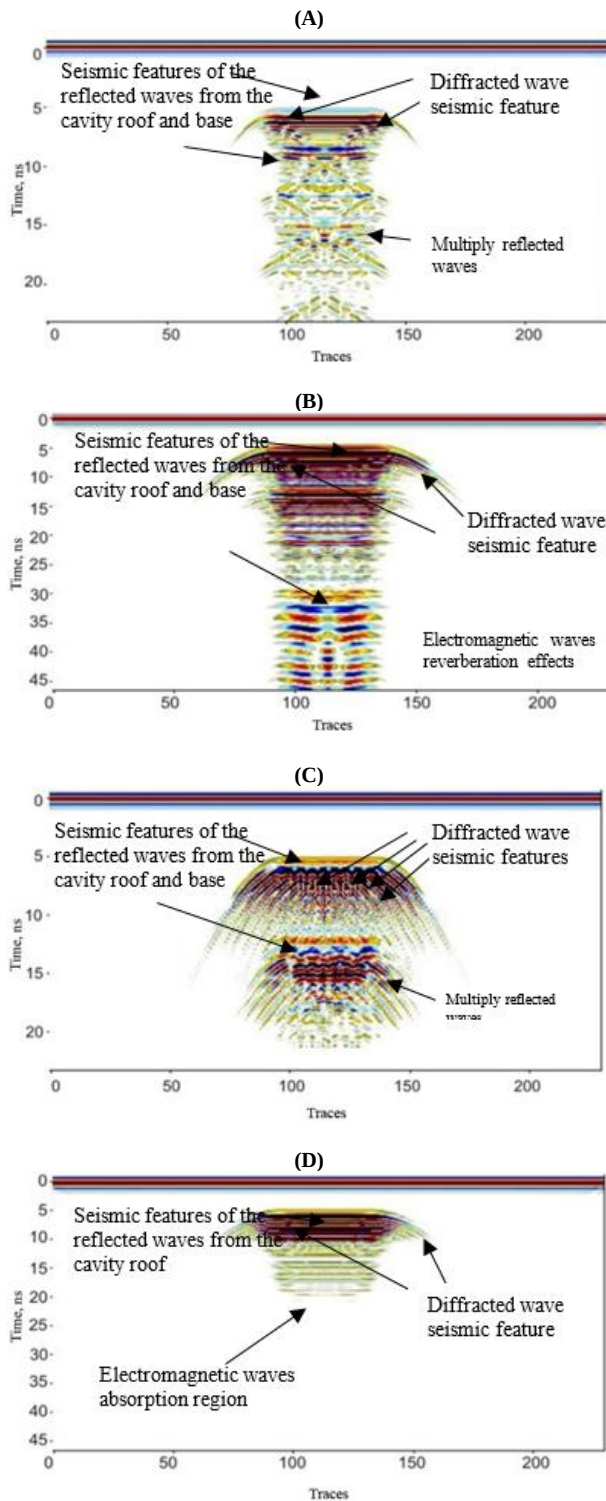


Fig. 4: Basic Electro Physical 2D Model of Cavity Filled with: A) Air; B) Water; C) Sandy Cobble; D) Clayish Soil Summary Table 1 Has Been Prepared for Convenience of Represent-Ing the Electromagnetic Wave Fields Kinematic Characteristics.

Table 1: The Summary Table of the Various Materials Electromagnetic Wave Fields Kinematic Characteristics at A Cavity Constant Geometry on Frequency of 700 MHz

Material type	Kinematic characteristic			
	v [cm/ns]	$2t_r$ [ns], roof	$2t_b$ [ns], base	λ [cm]
Air	30	5.91	8.59	42.8
Water	3.33	4.94	29.31	4.76
Clay rocks	6	5.08	-	8.57
Crushed rocks	12.2	5.18	11.8	17.5

The air is a high-velocity medium as per Table 1, and it has the maximum wave length therein, so, the void, which depth is less than 20 cm, will not be discernible in the wave fields for this frequency

range. The water, on the contrary, is a low-velocity medium with a minimum wavelength and the cavities with the depth being in excess of 2.5 cm will be clearly reflected within the wave electromagnetic field on a frequency of 700 MHz.

Since a geological environment containing the cavity shall be considered as an isotropic one, and then, having the velocity of the electromagnetic waves within the cavity and the arrival times are known, the cavity depth (Δh) can be calculated.

$$\Delta h = \frac{v \cdot (2t_n - 2t_r)}{2}$$

However, on the real radargrams, the electromagnetic waves propagation velocity inside the cavity is unknown and it is not even always possible to distinguish the desirable reflected waves because of serious interference. The analysis of dynamic characteristics of the electromagnetic wave field is an alternate key for solving the problems of determining the cavities parameters.

3.4. Dynamic characteristics of wave electromagnetic fields

The structure of electromagnetic wave field is similar to that of seismic survey wave fields, but, due to differences in nature of elastic and electromagnetic waves, wave field parameters should be considered separately.

Dynamic characteristics of electromagnetic fields include the following:

- Electromagnetic waves amplitudes;
- Electromagnetic waves phases;
- Signal spectrum central frequencies.

The increased values area of the electromagnetic waves amplitudes is observed in the cavity area on the received theoretical radargrams regardless of the filling material. The increased values area of the amplitudes serves as a marker indicating the presence of electromagnetic wave fields anomaly.

The analysis of the electromagnetic wave field spectra in various cavity filling materials has been performed according to the obtained basic models (Fig. 5).

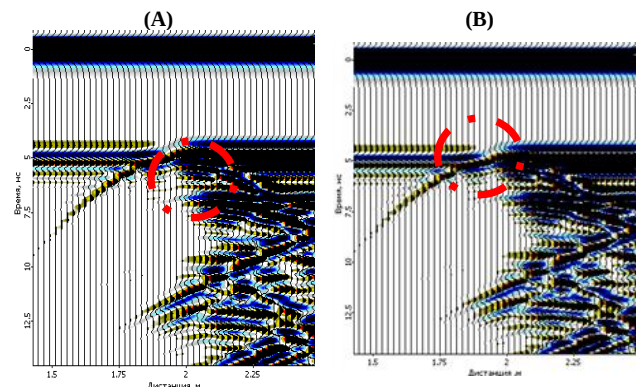


Fig. 5: Theoretical Radargrams of Electro physical 2D Air Filled Cavity Model (A) With a Manifested Phase Inversion Effect; and Water One (B) Where the Phase Inversion Effect Is Missing.

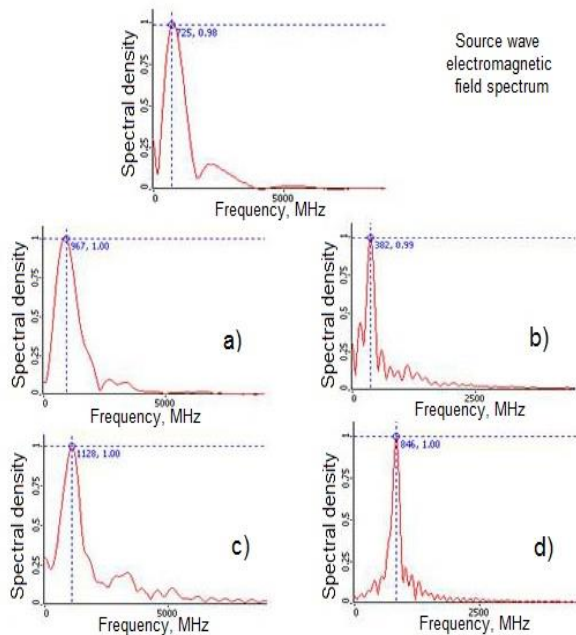


Fig. 6: Spectra of Theoretical Wave Electromagnetic Fields for Different Cavities Filling Materials: (A) Air (B) Water (C) Sandy Cobble and (D) Clayish Soil.

From Fig. 6, there the conclusion may be drawn that the increase of the probing pulses central frequency is observed while an electromagnetic wave transfers from the medium with lower transfer velocity to the one with the higher one (e.g. sand-crushed rock), and conversely, the central frequency decrease is observed during the transfer from the medium with higher transfer velocity to the one with the lower one.

4. Researches of electromagnetic wave fields of real sites

GPR investigations of the cavities have been conducted at the upstream side of the Votkinsk Hydroelectric Power Station (Figures 2 and 3) for assessing the similarity between the calculated and experimental electromagnetic wave fields. A natural cavity formed under the slabs of reinforced concrete of the upstream side protection is located at this site. The contours and the depth of this cavity are known. The depth of the cavity under the slabs is 38 cm and its length along the profile is equal to 1.5 m. The void has manifested itself on the radargram in the form of a bright intense local area of the electromagnetic waves reverberation.

The possibility of physical simulation performance via forming an artificial cavity of the required dimensions under the slabs is implemented at this site. Georadar survey was being performed along the profile constructed over the void which depth was consistently reducing from 35 cm as a result of sand filling and leveling at its bottom. Void depths were 15 cm, 25 cm and 35 cm. Ground penetrating radar sections reflecting the artificial void dimensions in plan view and in the depth are shown in Fig. 7. The void is schematically shown in the sections in the form of an ellipse which size corresponds to the void depth in vertical direction.

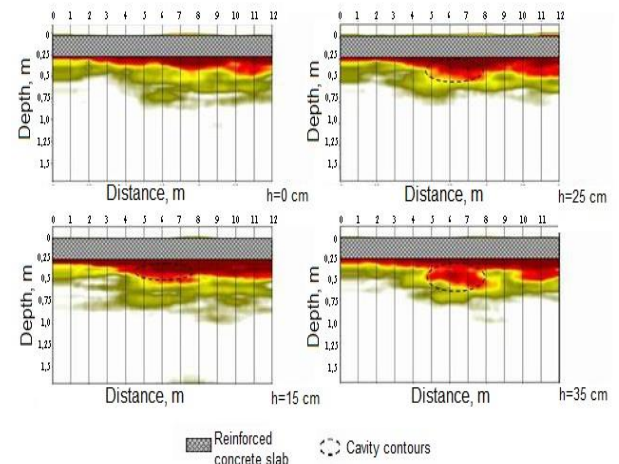


Fig. 7: Energy grams of Artificial Cavities with Various Vertical Dimensions ($H=0, 15, 25, 35$ Cm).

The transition from the electromagnetic field amplitude to frequency has been implemented using Fourier transform. The transition to frequency makes it possible to detect changes in the medium, as well as the transition from one medium to another one.

Dynamic periodogram section (Fig. 8), which clearly shows the express rise in frequency during transition from a solid medium into a cavity filled with air, was obtained as a result of the work in the STATISTICA© program.

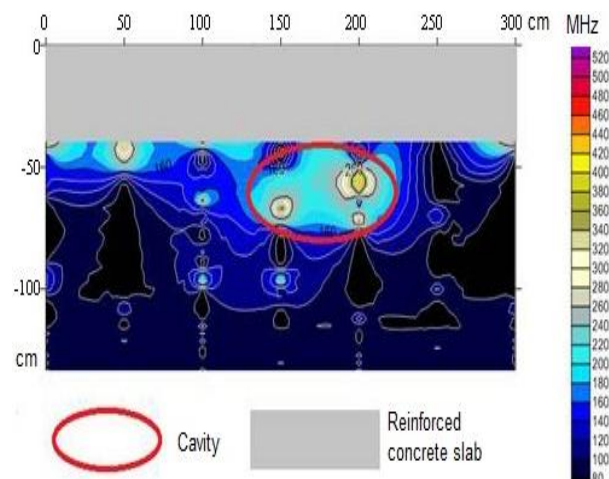


Fig. 8: period gram Characterizing the Shifts of the Electromagnetic Waves Central Frequencies Spectrum within the Cavity.

5. Conclusions

Based on the results of the performed mathematical and physical modeling, the following conclusions can be drawn:

- At the transfer of electromagnetic wave from lower velocity medium into (for example, sand-crushed stone) a growth of center frequency of direct impulses is observed, and vice versa, decrease of center frequency at transfer from higher velocity medium into lower one;
- In case of transfer of electromagnetic wave from the lower velocity medium into the higher one (for example, sand-air), an inversion effect of wave phase is observed (Fig. 3a), whereas at transfer from higher velocity medium into the lower one (for example, sand-water) phase inversion effect is absent (Fig. 5b);
- In the obtained dynamic section (Fig. 8), the area of shift of central frequencies spectrum of wave electromagnetic field, which describes cavity position and dimensions in the section, namely cavity width is 40 cm, length is 100 cm.

References

- [1] Alpin, L.M., Daev, D.S., Karinsky, A.D. (1985): The theory of the fields applied in the exploration geophysics. Nedra, Moscow.
- [2] Boganik, G.N., Gurvich I.I. (2006): Seismic survey: College Textbook. Well Researchers' Association publishing house, Tver.
- [3] Daniliev S.M. (2011): Justification of technique of ground penetrating radar surveys of geotechnical sites destruction areas. D.Phil. Thesis. Saint Petersburg.
- [4] Deryuga, A.M. (2002) GPR method of engineering surveys in the urban economy. *Polimergaz*. 3(23), 35-37.
- [5] Efimova, N.N. (1999): GPR studies when solving geophysics engineering problems: abstract of the thesis of Ph.D. in Engineering Science. Saint-Petersburg.
- [6] Georadar control program and visualization of GeoScan 32 output data: Illustrated Manual. (2005): Logis, Zhukovsky.
- [7] Giannopoulos A., (1997): The investigation of Transmission-Line-Matrix and Finite-Difference Time-Domain Methods for the Forward Problem of Ground Probing Radar, D.Phil thesis, Department of Electronics, University of York, UK, 264-271.
- [8] Glazunov, V.V., Efimova N.N. (2001): Assessment of the structural layers and road bed of motor road according to GPR data. *Exploration and conservation of mineral resources*, 3. 39-42.
- [9] Izyumov, S.V., Druchinin S.V., Voznesensky A.S. (2008): Theory and methods of GPR: training manual for universities and colleges. Mining book, Publishing House of the Moscow State Mining University, Moscow.
- [10] Kalinin, A.V., Vladov M.L., Shalaeva N.V. (2003): Evaluation of GPR investigations propagation distance based on the classical theory. *Bulletin of Moscow State University, Geology Series*, No.3, pp. 44-48.