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EVALUATION OF SIGNAL PROPERTIES WHEN SEARCHING FOR CAVITIES IN SOIL UNDER CONCRETE SLABS BY RADIO DETECTION STATIONS OF SUBSURFACE INVESTIGATION

Gennadiy V. RUDIANOV[1], **Evgeny I. KRAPIVSKY**[2], **Sergey M. DANILEIV**[2]
[1] *Mikhailovskaya Artillery Military Academy, Saint-Petersburg, Russia*
[2] *Saint-Petersburg Mining University, Saint-Petersburg, Russia*

A method of localization of concealed cavities on the basis of studying of the reflected electromagnetic impulses is considered in the paper. An issue of early detecting of concealed cavities in engineering facilities is a critical one due to a significant influence on further serviceability of a structure. Problems of localization of concealed cavities in the soil body under the concrete slabs of hydropower stations were studied; the results of ground radar detecting investigations of the cavities, physical simulation of a cavity as well as a mathematical modeling of a reflected signal are presented.

Modern subsurface radar detection provides methods which allow to reliably detect concealed cavities in the soil. However, it is possible only in case of a clear boundary between the adjacent layers that conditions a jump of dielectric permeability. In the result of an abrupt change of dielectric permeability a reflected wave occurred; the existence of subsurface heterogeneity is conditioned by the properties of this wave. Moreover, the greater is the difference between the values of dielectric permeability in the adjacent layers, the larger amplitude the reflected wave will have. If the cavity is at the stage of forming, i.e. it is filled with the soil of reduced density, then there is no clear boundary at the border of the layers which will condition a gradual change of dielectric permeability with depth. In this case an amplitude of a reflected wave will be minimal and a formation signal will be masked out by jamming signals reflected from various heterogeneities. In such case to determine a cavity at the stage of forming seems to be impossible. To determine poor signals an analysis of a phase of a reflected signal may be used; phase alters in compliance with the reflection coefficient change pattern. The article contains information about signals reflected from the heterogeneities and a conclusion regarding a possibility of detecting cavities in the soil on the basis of a method of coherent processing of signals is made.

Key words: ground radar detector, reflection coefficient, dielectric permeability, antenna directivity diagram, dielectric loss tangent, phase detector, coherent processing

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Introduction. In the process of a long-term service load conditions a formation of cavities to be concealed under the concrete slabs become possible. The existence of such cavities contributes to deformation of concrete slabs and even to their fracture, that is why early recognition of the concealed cavities in the subsoil of the hydraulic engineering structures is a crucial task.

To detect the cavities in the soil a radar method is widely used at the moment; the method supposes the following [9]. Short electromagnetic impulses are formed with the help of generator to be addressed to antenna, converted into radio wave and radiated into the underground space.

A concrete slab lies directly on the ground with certain electrical characteristics. A cavity filled with water, air and mixture of soil and water or soil and air may be formed in the subsoil. The fact of existing or absence of a cavity should be proven. For this purpose a radio locator is used; with the help of antenna unit it radiates electromagnetic impulses to be perpendicular to the plain surface of a slab. During searching for cavities the antenna unit is moved over the surface of the slab.

The antenna should be placed in the way that the antenna directivity diagram (ADD) was perpendicular to the ground surface. A wave propagating in the soil is reflected from heterogeneities which are represented as a contact between reinforced concrete slab and air-filled cavity, and is received by antenna where it is converted into the electric signal to be further addressed to the receiving module. The existence of a cavity may be proven by reflected impulse.

The exploring space may be represented as a two-layer model in which the first layer is a concrete slab with certain electrical characteristics and the second layer is a cavity concealed under the slab; the characteristics of a cavity are not known. The structure and composition of a cavity filling (soil, water, air) is determined by its electrical characteristics. The values of dielectric permeability of the soil for various radiation frequencies are used as electric characteristics.

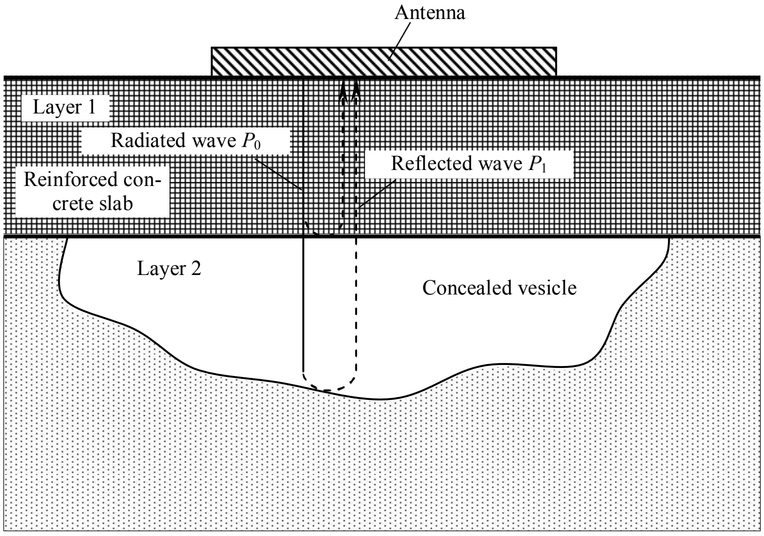

Fig.1. A scheme of reflection of electromagnetic waves from layers

A three-layer model of half-space: reinforced concrete slab – concealed cavity – soil plays a role of a studied half-space (Fig.1).

A radio wave which is radiated perpendicular to the studied layer is reflected from the boundary «concrete slab-cavity» and «cavity-soil» and the resultant signal is received by antenna. If there is no cavity there will not be a reflection as well, owing to close values of dielectric permeability of concrete and soil. For example, for sandy soil ε = 4-6, for concrete ε = 4-10 [6]. Consequently, there is no cavity. However, an extensive reflection conditioned by the existence of steel rebar, will be observed in any case. A similar reflected signal is cut by strobing.

A strength of the reflected signal is determined by the reflectance factor which, in turn, depends on the relation between the values of dielectric permeability of the layers [11]:

$$\dot{R}_{1-2} = \frac{\sqrt{\dot{\varepsilon}_1} - \sqrt{\dot{\varepsilon}_2}}{\sqrt{\dot{\varepsilon}_1} + \sqrt{\dot{\varepsilon}_2}}, \tag{1}$$

where $\dot{\varepsilon}_1$, $\dot{\varepsilon}_2$ – complex dielectric constants of the first and the second layers.

The greater the relation between the dielectric permeability of the layers is, the higher the strength of the reflected signal from the boundary of the layers will be. The structure of the reflected signal depends on the boundary between the layers: the more abrupt boundary is, the more accurate the determination of the depth of this zone will be [5, 7].

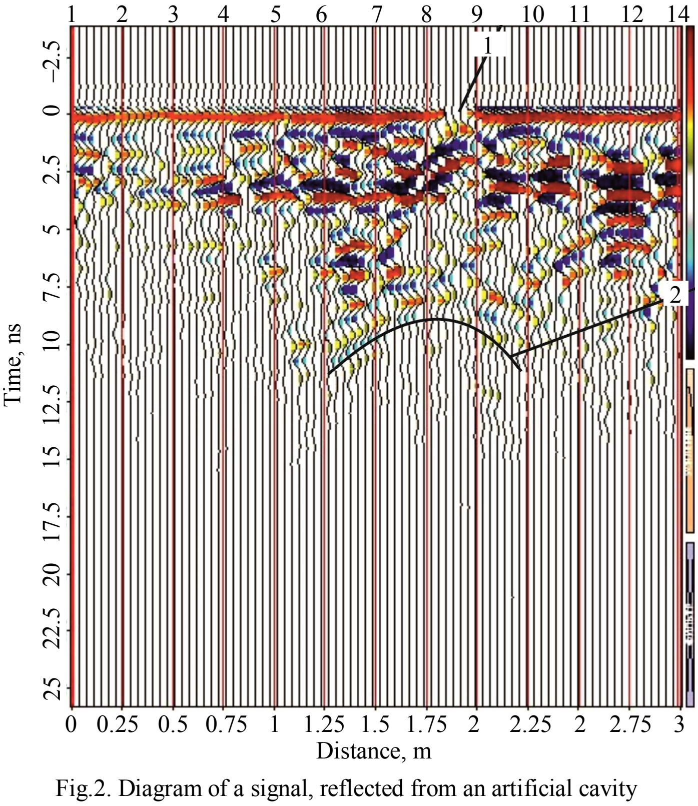

Fig.2. Diagram of a signal, reflected from an artificial cavity
1 – a hole; 2 – reflection from a cavity

Research objective. A cavity under the slab which is in the process of formation is represented by the soil with low density which may be filled with water or air. A dielectric permeability of such a cavity changes gradually from ε_1 to ε_2. In such a case, the equation (1) is impossible to use. The values of dielectric permeability within the elementary layers slightly differ from each other and from the surrounding soil which conditions small value of the reflected signal comparable with the noise signals. The stated above fact do not allow to detect the cavity with the sufficient reliability.

Earlier the experimental ground radar studies regarding the localization of the cavities under the concrete slabs of the hydro-electric power station were performed [7]. A ground radar ZOND-12E with the center frequency of direct impulses 1000 MHz was used as radar equipment.

A studied model of the section is represented as reinforced concrete slabs of 30 cm thickness lying on the sandy soil foundation. A slab is fabric-reinforced with the metal rod of 30 mm diameter and a mesh width of 30 cm.

For the purpose of physical simulation of the concealed cavities across slabs an artificial cavity of 1 m length and 30 cm thickness was made. Ground radar was moved along the surface of the slab with simultaneous recording of the signal.

A graphical view of a diagram of a signal referring to the section of 3 m length near the cavity is shown in Fig.2. Approximately on the distance of 2 m there is a hole at the boundary of the slabs. During time delay of 10-12 ns the reflection from the cavity may be detected.

As the relative dielectric permeability of the sand is ε = 10 for the frequencies 0.4-1 GHz [13], then in accordance with the following

$$h = \frac{c\tau}{2\sqrt{\varepsilon}}, \qquad (2)$$

where c – velocity of propagation of the radio waves in the air, time delay $\tau = 10$ ns matches with the 1.5 m depth.

Fig. 3 shows a ground radargram of the signals reflected from the natural cavity which is at the stage of forming i.e. soil softening took place in the studied area. This cavity was detected by means of direct measurements in the borehole and in the holes between the slabs; its length is more than 100 cm and thickness is equal to 60 cm.

A cavity is detected within the interval of 9-11 m. As reflected by the figure, a set of reflected signals do not allow to validate reliably the existence of the cavity.

Consequently, major drawback of classical ground radar studies consists in the low probability of detecting the underground cavities and especially those cavities which are being formed.

Hence, the development of the method which would help to increase a reliability of detecting the cavities under the reinforced concrete slabs of hydro power stations is an important issue.

Method justification. For the purpose of dealing with the stated above task a method of radar detection may be used; this method allows to study the phase of the reflected signal which depends on the dielectric permeability of the soil and, thus, the reflection coefficient of the radio wave when it is reflected from the system of the layers [1, 4].

A mathematical simulation technique is used to form the sounding signal and the reflected one.

A signal formed by ground radar ZOND-12E was taken as a prototype of the sounding signal during the process of simulation. This signal is presented as one half-wave of harmonic vibration

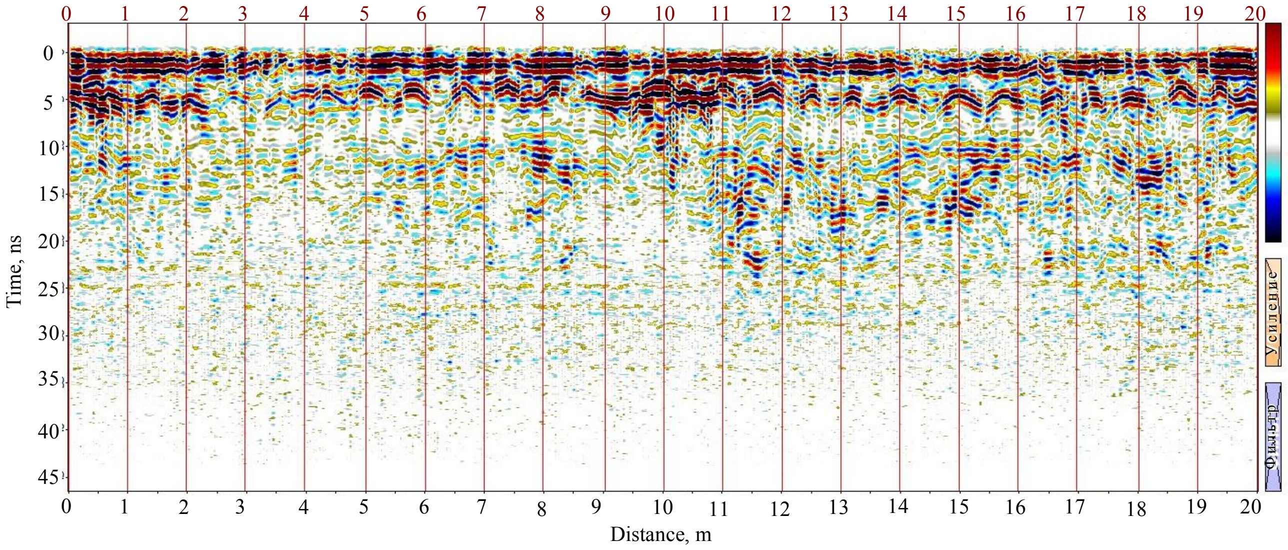

Fig. 3. Diagram of a signal reflected from natural cavity

of negative value at the carrier frequency which is determined by the replaceable antenna module.

The following expression was used as a mathematical model of sounding signal [5]:

$$s(t) = \cos(2\pi ft)\sin^2(2\pi ft), \qquad (3)$$

where f – center frequency of ground radar radiation, $f = 2$ GHz.

In contrast to the original source, the second multiplier of the argument contains the time variable t.

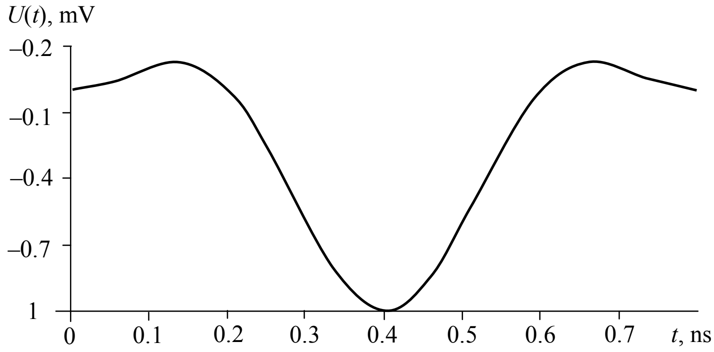

Fig.4. Model of a sounding signal

The signal which was formed is shown at Fig.4.

The reflected signal with respect to time variation may be described by the following equation [5]:

$$s(t) = \sum_{j=0}^{\infty} r_{j,j+1} \int_{-\infty}^{+\infty} \left[\int_{-\infty}^{+\infty} s(t) e^{-2\pi ift} dt \right] e^{-2\pi if\left[t + \frac{2}{c}\int_0^{z_j} n(z)dz\right]} df, \qquad (4)$$

where $r_{j,j+1}$ – reflection coefficient from the boundary of j-layer; f – frequency; z – density; $n(z) = \sqrt{\varepsilon(z)}$ – refraction coefficient; $\varepsilon(z)$ – functional relation between dielectric permeability and depth of density.

Refraction coefficient r is determined as the following

$$r_{j,j+1} = \frac{n(z_j) - n(z_{j+1})}{n(z_j) + n(z_{j+1})}. \qquad (5)$$

As a preliminary, let us consider the expression for the reflected signal in case of existing cavity which may be filled with air or water.

If there is a formed cavity under the concrete slab then the values of dielectric permeability ε for various layers (air, water, concrete, soil) may considered to be constant values (not dependent on the depth z). Thus, the integral in the exponent of the equation (4) may be expressed as the following [2]

$$\frac{2}{c}\int_0^{z_j} n(z)dz = \frac{2nz_j}{c}, \qquad (6)$$

where z_j – thickness of a layer.

This integral has the sense of the time interval during which a direct impulse propagates there and back again within the layer. The coefficient n which is referred to refraction coefficient and is dependent on the dielectric permeability ε should determine the increase of time needed for the impulse to propagate depending on the medium type. Taking into account this allowance, the reflected signal (4) may be written as the following

$$s(t) = \sum_{j=0}^{\infty} r_{j,j+1} \int_{-\infty}^{+\infty} \left[\int_{-\infty}^{+\infty} s(t) e^{-2\pi ift} dt \right] e^{-2\pi if\left[t + \frac{2nz_j}{c}\right]} df. \qquad (7)$$

A complex quantity in the exponent determines the periodic character of the reflection coefficient depending on the depth [6, 8].

A simulation of the reflected signal was performed for the values of dielectric permeability of concrete, air and sand which is respectively equal to $\varepsilon_c = 6$, $\varepsilon_a = 1$, $\varepsilon_s = 30$ (for waterlogged sand). Thus, the refraction coefficients from the borders of the layers to be determined by (5) are equal to: for layer «concrete-air» $r_{1,2} = 0.42$, for layer «air-sand» $r_{2,3} = -0.69$.

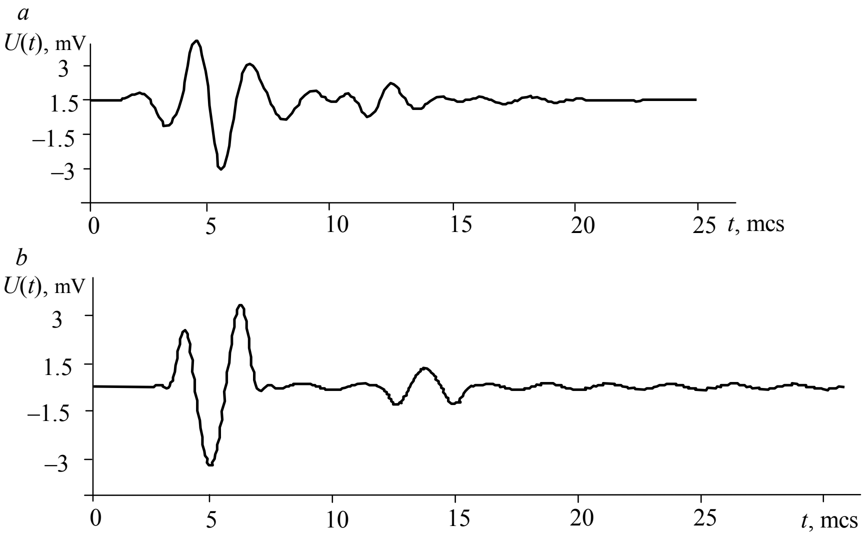

Fig. 5. Type of a reflected signal: *a* – simulated reflected signal; *b* – real reflected signal ($\varepsilon_c = 6$, $\varepsilon_a = 1$, $\varepsilon_s = 30$)

Fir.5, *a* shows a view of the simulated reflected signal on the basis of previously given data for the cavity of 1 m length and 40 cm depth; the thickness of a concrete slab is 25 cm.

Considering the radargram, the first impulse represents a reflection from the lower surface of the concrete slab (border «concrete-air»), the second impulse is a reflection from the bottom of the cavity (border «air-sand»). A transition from one layer to another is prominent (dielectric permeability is jumping) and, consequently, the impulse reflected from the bottom of the cavity may be clearly seen. The value of time interval between the first and the second impulses is determined by the distance between the lower surface of the concrete slab and the bottom of the cavity.

Fig.5, *b* shows a real signal obtained during sounding a cavity of 1 m length and 30 cm depth with the help of ground radar ZOND-12E. Thickness of a concrete slab was equal to 30 cm.

Comparing the figures, a good convergence between a model and a real signal is seen.

The dielectric permeability of sand drastically depends on degree of water saturation; also the dielectric permeability of the sand decreases when the water volume goes down. When the water content in the sand is equal to 16 % the dielectric permeability is $\varepsilon_s = 14$ [11]. In this case, the coefficient of reflection from the boundary of the layers «air-sand» is $r_{2,3} = -0.58$.

Considering that the value of dielectric permeability of sand decreased and, consequently, the reflection coefficient also fell as well as the amplitude of the reflected impulse. However, the existence of the reflected signal allows to detect the concealed cavity and the time location of the reflected signal specifies the thickness of the studied cavity.

Now we may consider how the reflected signal changes if the cavity is filled with water. The dielectric permeability of water is $\varepsilon_{wat} = 81$. Thus, the coefficient of reflection from the boundary «concrete-water» is equal to $r_{1,2} = -0.57$, the coefficient of reflection from the boundary «water-sand» (if $\varepsilon_s = 30$ for sand) is equal to $r_{2,3} = 0.24$.

Fig.5 shows that the phases of signals changed for 180° which may be explained by the change in signs of the values of reflection coefficients in the formula (5).

Therefore, if the dielectric permeability (and the refraction coefficient as well) jumps then there is a crucial possibility that the existence of the reflected signal may predetermine the concealed vesicle. And the greater the reflection coefficient is, the larger the amplitude of the reflected signal.

The issue of how the view of a signal reflected from the vesicle at the stage of forming, i.e. with low density of a soil, will change should be considered.

A dielectric permeability of such a cavity may be represented as a model performing a function of dielectric permeability gradually changing from the start value ε_1 up to the end value ε_2. The expression [5] may be used as such a model

$$\varepsilon(z) = \varepsilon_1 + \frac{(\varepsilon_2 - \varepsilon_1)\exp\left(\dfrac{z-d}{\mathrm{tg}\delta}\right)}{1+\exp\left(\dfrac{z-d}{\mathrm{tg}\delta}\right)}, \tag{8}$$

where ε_1, ε_2 – start and end value of dielectric permeability of a layer; tgδ – dielectric loss tangent; z – current value of a depth; d – thickness of a cavity.

According to the equation (8) dielectric permeability of a cavity monotonically increases with the depth which imitates a cavity where a soil in the upper its part has minimal density (filled with air), and in the bottom part the density is maximal.

A dielectric loss tangent tgδ for sandy soil was taken as 0.01 for simulation procedure. A function of dielectric permeability conforming the equation (8) is represented as a monotone increasing function.

A form of a reflected signal is determined by the reflection coefficient function. However, a gradual change of dielectric permeability conditions monotonous change of reflection coefficient with depth. For this reason, the development of an equation in the analytical form for the function of coefficient of reflection and depth for heterogeneous layer is rather complicated and may be obtained only for some types of simple functions (exponential, linear distribution). Therefore, according to recommendation [11], to determine a type of a signal reflected from various elements of a cavity with optional form of a function of dielectric permeability it is necessary to replace the whole volume of a cavity with the N elementary layers with constant dielectric permeability. In this case the reflection coefficient depending on the depth [5]

$$R(z) = r_{1,2} + \sum_{j=2}^{N+2} r_{j,j+1} \mathrm{e}^{2ik\int_0^z n(z)dz}, \qquad (9)$$

where $k = 2\pi/\lambda$ – vacuum wave number; λ – length of a radiating wave; N – number of elementary layers.

Coefficients of reflection from the boundaries between elementary layers $r_{j,j+1}$ are determined by the equation (5).

A function of reflection coefficient calculated for the layers $N = 16$ by formula (9) is presented at Fig.6.

As we may see, in case the dielectric permeability is changing gradually the maximal value of reflection coefficient is equal to 0.06 which is dramatically less in comparison with the case of stepped variation of dielectric permeability (for the boundary «concrete-water» $r = -0.57$).

A partition of a heterogeneous layer in discrete layers with constant dielectric permeability may jam the form of a function of reflection coefficient, however, in case of $N = 16$ number of layers the empirical form of the reflection coefficient function depicts the theoretical form precisely enough. Analyzing the graph at Fig.6, we may suppose that for the function of dielectric permeability (8) a function of reflection coefficient is a derivative of function of dielectric permeability (Fig.7).

Comparing the graphs we may conclude that in case of number of layers $N = 16$ the empirical form of function of reflection coefficient depicts the theoretical form rather precisely.

As is obvious from the graph (Fig.7), the length of a reflected signal spread

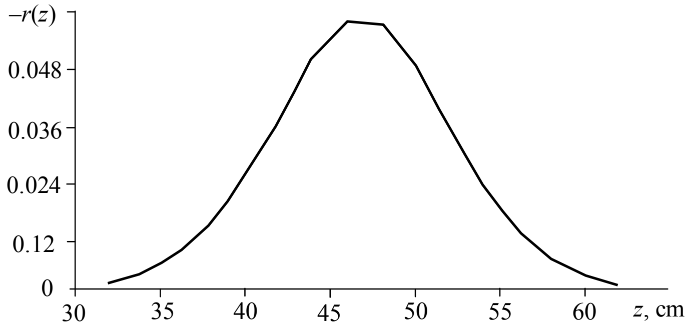

Fig.6. empirical function of reflection coefficient calculated for $N = 16$ layers

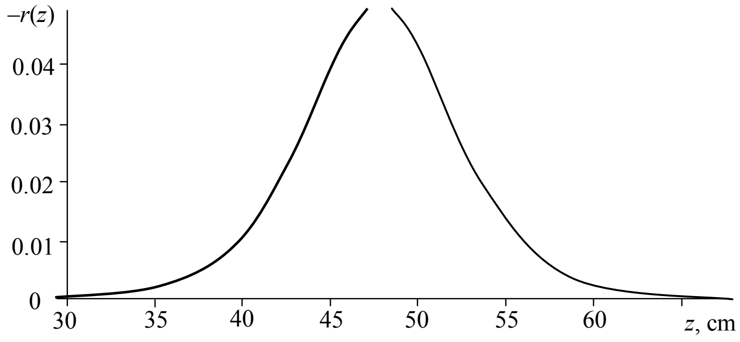

Fig.7. Theoretical function of reflection coefficient

(from 7 to 15 mcs) and the amplitude decreased (due to decrease of the reflection coefficient) which worsens the conditions for detection of a concealed cavity.

We may consider how the conditions of signal reflection from the cavity with heterogeneous filling will change regarding the dielectric tangent loss increase up to 0.015.

Applying the value of tgδ = 0.015 to the equation of dielectric permeability (8) we obtain a function the graph of which is presented in Fig.8.

A comparison of graphs at Fig.7 and Fig.8 showed that in the latter case the incline is reduced, i.e. the effect of smoothing the boundaries of dielectric permeability of the layers took place.

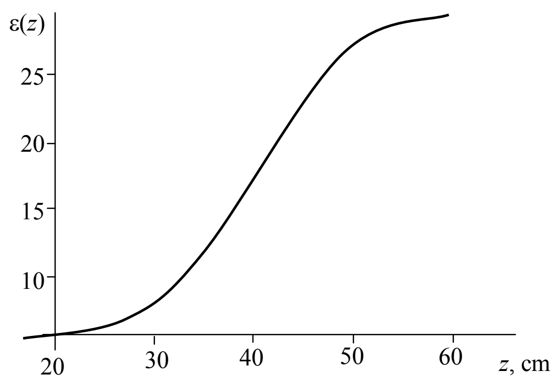

Fig.8. Function of dielectric permeability for tgδ = 0.015

The calculations showed that the maximum value of reflection coefficient reduced from 0.06 to 0.04. Besides, the functions became more gentle. If the function of reflection coefficient if rather gentle, a signal reflected from the cavity is almost completely undetectable which does not allow to detect the concealed cavity.

Consequently, we may conclude that the best condition for detecting the reflected signal is a jump variation of dielectric permeability at the boundary of two medium. The coefficient of reflection from the boundary will reach maximum value. Moreover, the greater the difference between the values of dielectric permeability of the adjacent layers, the greater the reflection coefficient will be [3]. In case of gradual change of dielectric permeability (for instance, a cavity is partly filled with some soil), a reflected signal may not be detected against the background of other reflections which excludes a possibility of detecting a concealed cavity.

For study of a possibility of detecting concealed cavities with the gradual change of dielectric permeability a following expression for a reflected signal may be considered [9]:

$$E = (1 - r_{1,2}^2) r_{2,3} \exp(-2\alpha z) \exp(-i\omega 2z / v_\text{p}) , \tag{10}$$

where $r_{1,2}$, $r_{2,3}$ – coefficients of reflection from the upper and lower boundaries of a cavity; α – attenuation constant; z – depth (current coordinate); ω – an average frequency of the antenna module; v_p – phase velocity of a radio wave propagation inside a layer,

$$v_\text{p} = c / \operatorname{Re}\sqrt{\dot{\varepsilon}} . \tag{11}$$

Substituting an equation for a reflection coefficient (9) in (10) we obtain

$$E(z) = (1 - r_{1,2}^2) \left(r_{1,2} + \sum_{j=2}^{N+2} r_{j,j+1} \mathrm{e}^{2ik\int_0^z n(z)dz} \right) \exp(-2\alpha z) \exp(-i\omega 2z / v_\text{p}) , \tag{12}$$

where N – number of elementary layers.

These data indicate that the phases of signals reflected from the elementary layers may change by pattern:

$$\varphi(z) = \operatorname{Re}(2k \int_0^z \dot{n}(z) dz) , \tag{13}$$

where $k = 2\pi/\lambda$ – wave number.

If there is no cavity (a homogeneous soil is under the slab) then the dielectric permeability is constant [14]. In this case, a phase of a signal reflected from the heterogeneities changes over the depth with constant velocity. If there is a cavity at the stage of forming under the slab, i.e. it may be partly filled with soil of low density, then the dielectric permeability will change by a certain pattern (a nonlinear pattern in general). Thus, the signal phase will change by the pattern corresponding with the soil properties, but this pattern will not be a linear one. If there is no

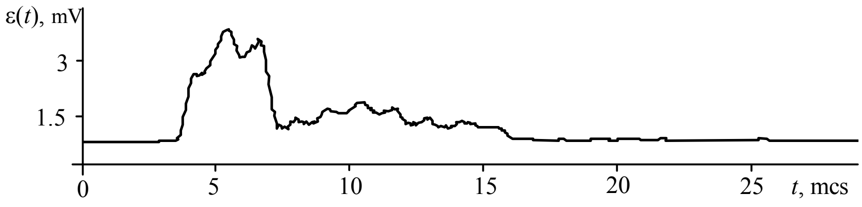

Fig. 9. Signal after a coherent processing tgδ = 0,01

cavity, i.e. there is a homogeneous soil under the slab, then the phase of a reflected signal may be determined by the equation (6) and change according to the linear pattern, i.e. a phase incursion is conditioned only by the depth change.

Consequently, analyzing the pattern of phase change, a concealed cavity may be detected. To determine the pattern of phase change, a synchronous (phase) detector [10] may be used; a reflected and a vibroseis signals will be addressed to this detector. A harmonic voltage with the frequency equal to a center frequency of radar radiation is used as a vibroseis signal. An equivalent scheme of a phase detector may be represented as a multiplicator which performs a multiplication of a reflected and vibroseis signals and an integrator smoothing fluctuations of a signal output.

In compliance with the presented equivalent scheme, a voltage occurs at the output of the synchronous detector

$$u_{\text{p.d}}(t) = \frac{1}{T}\int_0^T u_{\text{s}}(t)u_{\text{vib}}(t)\cos(\Delta\varphi(t))dt, \tag{14}$$

where u_{s}, u_{vib} – voltage of a signal and vibroseis voltage; T – averaging interval; $\Delta\varphi$ – a phase of the reflected signal.

An averaging interval should be chosen to avoid the interference of the form of output signal. When the studies were performed $T = 1/f_0$, where f_0 – average frequency of ground radar radiation.

For the purpose of determining a possibility of detecting concealed vesicles at the stage of forming (with the gradual change of dielectric permeability) a coherent processing of a reflected signal was made in compliance with the equation (14). For a signal shown in Fig.5 an output signal after a coherent processing is demonstrated in Fig.9.

As seen in Fig.5 and 9, a reflected signal contains a reflection from the cavity in the form of amplitude increase of a signal at the output of phase detector between 7-15 mcs which is conditioned by the depth of a cavity. An increase of an amplitude of a signal is conditioned by the change in phase of the reflected signal by the pattern (8).

When there is no cavity, a change in signal phase is conditioned only by the depth change as the dielectric permeability is constant. Thus, the radargram shows only a reflection from the boundary «concrete-sand», then the noise bursts reflected from the miniscule heterogeneities of the soil are shown. The given radargram show that there is no any cavity under the slab.

Conclusions

The following conclusions should be made as the result of the performed studies:

1. The dependency of reflection coefficient and dielectric permeability in case of heterogeneous soil (when dielectric permeability changes gradually over the depth from ε_1 to ε_2) was studied. In case of gradual change of dielectric permeability (integral character) a function of reflection coefficient occurred to have a bell-shape, provided that the width of the function is determined by the velocity of dielectric permeability change.

2. The analysis of models of radar signals reflected from concealed cavities was performed. A justification of a possibility in principle of detecting concealed cavities in the soil at the stage of forming located under the concrete slabs with the help of ground radar on the basis of coherent processing of the reflected signals was performed.

3. A proposed method on the basis of coherent processing allows to increase the probability of cavities detecting owing to additional information – a phase of reflected signals.

4. A proposed method allows to determine a character of the material filling a concealed cavity under the concrete slab: a cavity filled with water or air-filled cavity. A proposed method refers to the group of nondestructive testing methods and do not require fracturing of concrete slabs, allowing to increase a reliability of cavities detecting (including those at the stage of forming) which appear under the concrete slabs.

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Authors: **Gennadiy V. Rudianov**, *Candidate of Engineering Sciences, Associate Professor, gen.r@mail.ru* (*Mikhailovskaya Artillery Military Academy, Saint-Petersburg, Russia*), **Evgeny I. Krapivsky**, *Doctor of Geological and Mineralogical Sciences*, *Professor*, *eikrapivsky@mail.ru* (*Saint-Petersburg Mining University*, *Saint-Petersburg, Russia*), **Sergey M. Daniliev**, *Candidate of Geological and Mineralogical Sciences*, *Associate Professor*, *daniliev@mail.ru* (*Saint-Petersburg Mining University*, *Saint-Petersburg, Russia*).

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