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MODELS OF CHANGES IN GEO-RADAR REGISTRATIONS CAUSED BY HYDROCARBON CONTAMINATION

MODEL ZMIAN W REJESTRACJACH GEORADAROWYCH WYWOŁANYCH ZANIECZYSZCZENIAMI ROPOPOCHODNYMI

The possibility of locating hydrocarbon contamination in soil is discussed. The following problems are considered:

- emission of geo-radar waves in a medium with fluctuating electrical properties,
- flow of mixture consisting of hydrocarbon contamination and water in inhomogeneous lithological strata,
- estimation of differences in the geo-radar signals structure from clean and contaminated areas and interpretation of the difference on the base of results obtained in the first two points.

Key words: hydrocarbon contamination, geo-radar method, inhomogeneous flow.

Lokalizacja zanieczyszczeń ropopochodnych w gruncie jest ważnym problemem ekologicznym. Istnieje podstawa empiryczna do stwierdzenia, że do tego celu może być wykorzystana geofizyczna metoda georadarowa. Artykuł jest poświęcony analizie możliwości zbudowania fizycznych modeli wiążących strukturę sygnałów georadarowych ze stopniem zanieczyszczenia gruntu materiałami ropopochodnymi. Taka analiza składa się z trzech części.

W pierwszej części przeanalizowano transmisję fal elektromagnetycznych dla częstotliwości georadarowych. Wskazano na skomplikowany charakter tego pola ze względu na:

- różne mechanizmy tworzenia polaryzacji elektrycznej dla różnych zakresów częstotliwości pól wywołujących to zjawisko,
- zależności charakteru tworzonych sygnałów georadarowych od częstotliwości,
- zależności transmisji fal georadarowych od przestrzennego rozkładu parametrów dielektrycznych i elektrycznych w ośrodku i ich anizotropii.

W drugiej części przedstawiono skomplikowane modele przepływów mieszaniny wody i ropopochodnego zanieczyszczenia. Wskazano na to, że zróżnicowana litologia utworów czwartorzędowych wpływa istotnie na sposób transportu zanieczyszczeń i może być

przyczyną tworzenia się lokalnych ich koncentracji oraz języków zanieczyszczeń w kierunkach zależnych od własności ośrodka, takich jak jego zapiaszczenie czy zawilgocenie.

W trzeciej części przedstawiono wynik rejestracji georadarowych prowadzonych w rejonach zanieczyszczonych i w rejonach czystych. Pokazano różnice w strukturze sygnałów georadarowych pochodzących z tych dwóch obszarów i różnice w ich widmach. Wskazano na możliwy związek pomiędzy takimi wynikami a analizowanymi poprzednio własnościami emisji fal georadarowych i rozkładem własności fizycznych w gruncie, w którym nastąpił przepływ zanieczyszczenia ropopochodnego.

Słowa kluczowe: zanieczyszczenia ropopochodne, metoda georadarowa, niejednorodne przepływy.

1. Introduction

The development of geo-radar methods, which are a recently advance, have resulted in its successful use in the location of environmental changes in the nearsurface soil properties, which are important for the ecology, and in the mining and construction industries.

Recognition of changes by this method depends on changes in permittivity and electrical resistivity, which cause significant changes in the propagation and reflection of geo-radar waves.

The permittivity of water is many times greater than that of air and thus geo-radar is often used to assess soil humidity.

Geo-radar methods may also be used to locate areas of hydrocarbon contamination in the ground. This application requires an analysis of the mechanisms that influence the appearance of the geo-radar signals in order to interpret them. The problem is rather complicated for the following reasons.

a) Transport of contamination is altered by different geological conditions, particularly changes in the water flow in specific conditions.

b) Changes in the permittivity and electrical conductivity of a porous medium contaminated with hydrocarbons must be recognised.

c) The resolution of the geo-radar images depends on the depth at which the contamination lies.

These problems are discussed in this paper.

2. The physical rules which form the basis of geo-radar measurements

The transmission of electromagnetic waves is described using the Maxwell equation.

$$\nabla \times \vec{E} = \frac{\partial \vec{B}}{\partial t} + \vec{M}$$

$$\nabla \times \vec{H} = \frac{\partial \vec{D}}{\partial t} + \vec{J}$$

Where \vec{E} , \vec{H} , \vec{B} , \vec{D} are vectors of electrical and magnetic field intensity and magnetic and electrical induction intensity, and \vec{J} and \vec{M} are vectors of electrical and magnetic currents density.

The electrical induction, which is a measure of the response of the medium to an external electrical field, depends on the frequency of that field.

It takes the form of arranging the electrical elements of the medium in accordance with the lines of the electrical field. This arrangement depends on the time-period in which the external field can actively influence the electrical elements: the frequency. The mechanisms of induction in the polarisation of different structural elements are shown in Fig. 1.

It is known that atoms consist of a nucleus surrounded by a cloud of electrons, which can be given a polarised configuration by an external field. This is known as electronic polarisation. In particles of different molecular binding (for example,

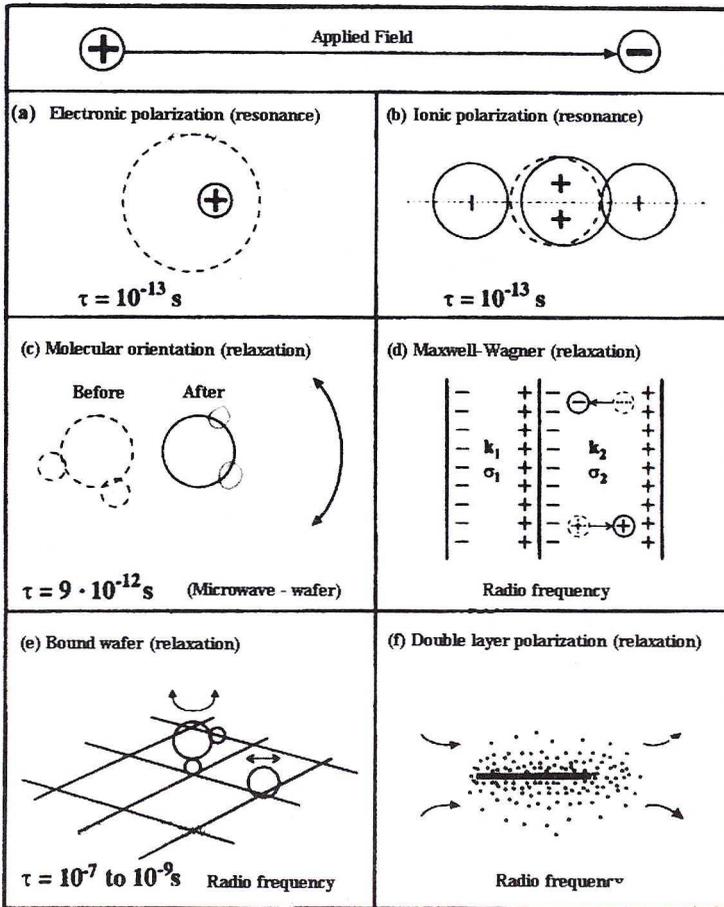


Fig. 1. Physical models of polarisation mechanism

water), the centres of gravity of the positive and negative charges are not located in the same place. An electrical dipole is constructed which, in an external field produces a particle field and an additional electrical field.

All types of inhomogeneities which exist in the crystalline structure of minerals are focuses for the gathering of charges on them, and this produces Debye's Field, correlated with the position of the particle, which is double-layer polarisation. The mechanisms of polarisation can be activated independently of each other but dependent on the frequency of the electrical field. For lower frequencies an approximation may be obtained with Debye's model (Zener 1948) Fig. 2.

$$\varepsilon_i(t) = \varepsilon_i^{(0)} \left[1 - \frac{1}{L_i} \sum_{i=1}^{L_i} \left(1 - \frac{\lambda_{iL}}{\tau_{iL}} \right) \exp\left(\frac{-t}{\tau_{iL}}\right) \right] H(t)$$

where $\varepsilon_i^{(0)}$ is a static value of the permittivity (the value of the permittivity over a long time-period). $H(t)$ — Heaviside's function, L_i — the number of mechanisms, λ_{iL} and — parameters of polarisation of the electrical field.

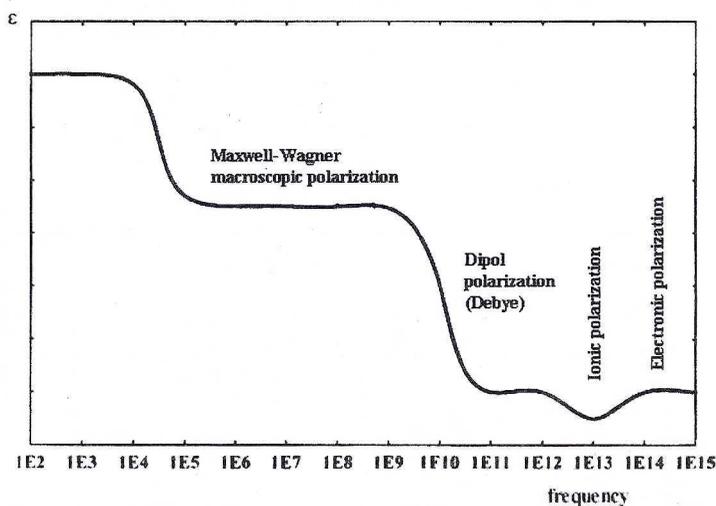


Fig. 2. The dependence of polarisation mechanism from frequency of electromagnetic waves

Similarly the changes of magnetic susceptibility may be estimated, depending on how the mechanisms of susceptibility are initiated.

$$\mu_i(t) = \mu_i^{(0)} \left[1 - \frac{1}{N_i} \sum_{N=1}^{N_i} \left(1 - \frac{\gamma_{in}}{\theta_{in}} \right) \exp\left(\frac{-t}{\theta_{in}}\right) \right] H(t)$$

where $\mu_i^{(0)}$ — static susceptibility, γ_{iL} and θ_{iL} — the relaxation times, N_i — the number of activated mechanisms.

For an electrical field which changes in time the intensity of the induced field takes the form

$$D(t) = \varepsilon \int_{-\infty}^{\infty} \delta(t-\tau)E(\tau)d\tau = \varepsilon \int_{-\infty}^{\infty} H(t-\tau)\frac{dE(\tau)}{d\tau} = \varepsilon^* \frac{\partial E}{\partial t}$$

where δ — the Dirac function, $*$ — convolution.

The intensity of the induced magnetic field is the convolution of the ε — parameter and the first time derivative of the electrical field intensity.

If the permittivity and the magnetic susceptibility are anisotropic, then

$$\vec{D} = \{\varepsilon(x, t)\} * \frac{\partial \vec{E}}{\partial t} \quad \vec{B} = \{\mu(x, t)\} * \vec{M}$$

where $\{\varepsilon(x, t)\}$ is relaxation tensor and $\{\mu(x, t)\}$ is a magnetic tensor of susceptibility.

It may be written in analogy to the consideration which was presented above

$$\vec{J} = \{\sigma\} * \frac{\partial \vec{E}}{\partial t} + \vec{J}_s$$

where $\{\sigma\}$ — electrical conductivity tensor, a \vec{J}_s is this part of electrical current, which appears in result of electrical potential existence.

Also the changes in electrical conductivity may be described using the formula

$$\sigma(t) = \sigma(0)|H(t) + \zeta\delta(t)| \text{ or } \sigma(t) = \sigma(0)[H(t) + \zeta\delta(t)]$$

where $\sigma(0)$ — static electrical conductivity, ζ — the relaxation ratio, $\delta(t)$ — Dirac function.

The following two vector equations are obtained

$$\nabla \times \vec{E} = -\mu^* \frac{\partial^2 H}{\partial t^2} + M_s$$

$$\nabla \times \vec{H} = \sigma^* \frac{\partial E}{\partial t} + \varepsilon^* \frac{\partial^2 E}{\partial t^2} + J_s$$

The orthotropic medium is introduced, in which the physical properties are different in two directions; horizontal and vertical. For μ , ε and δ their tensor values may be written as:

$$\mu = \begin{pmatrix} \mu & 0 & 0 \\ 0 & \mu_v & 0 \\ 0 & 0 & \mu_H \end{pmatrix} \quad \varepsilon = \begin{pmatrix} \varepsilon_v & 0 & 0 \\ 0 & \varepsilon_v & 0 \\ 0 & 0 & \varepsilon_H \end{pmatrix} \quad \sigma = \begin{pmatrix} \sigma_v & 0 & 0 \\ 0 & \sigma_v & 0 \\ 0 & 0 & \sigma_H \end{pmatrix}$$

With such relationships the electromagnetic field, in the Cartesian system $\vec{E}(E_1, E_2, E_3)$, $\vec{H}(H_1, H_2, H_3)$ is described by 6 equations

$$\begin{aligned}\frac{\partial E_2}{\partial x_3} - \frac{\partial E_3}{\partial x_2} &= \mu_H^* \frac{\partial^2 H_1}{\partial t^2} + M_1 \\ \frac{\partial E_3}{\partial x_1} - \frac{\partial E_1}{\partial x_3} &= \mu_H^* \frac{\partial^2 H_2}{\partial t^2} + M_2 \\ \frac{\partial E_1}{\partial x_2} - \frac{\partial E_2}{\partial x_1} &= \mu_V^* \frac{\partial^2 H_3}{\partial t^2} + M_3 \\ \frac{\partial H_3}{\partial x_2} - \frac{\partial H_2}{\partial x_3} &= \sigma_H^* \frac{\partial E_1}{\partial t} + \varepsilon_H^* \frac{\partial^2 E_1}{\partial t^2} + J_1 \\ \frac{\partial H_1}{\partial x_3} - \frac{\partial H_3}{\partial x_1} &= \sigma_H^* \frac{\partial E_2}{\partial t} + \varepsilon_H^* \frac{\partial^2 E_2}{\partial t^2} + J_2 \\ \frac{\partial H_2}{\partial x_1} - \frac{\partial H_1}{\partial x_2} &= \sigma_V^* \frac{\partial E_3}{\partial t} + \varepsilon_V^* \frac{\partial^2 E_3}{\partial t^2} + J_3\end{aligned}$$

3. Plane electromagnetic wave in soil

The transmission of the electromagnetic wave through the soil is considered, introducing a harmonic phase

$$\exp[i(\vec{k}\vec{r} - \omega t)]$$

where \vec{k} is a complex variable.

For a monochromatic wave in a homogenous medium the Green function, which is related to the scalar wave equation; the Helmholtz equation, has the form

$$g(r, \omega) = \frac{e^{ikr}}{r}$$

where r — the distance between the wave source and the point at which the solution is obtained.

Parameter k includes basic information about the propagation of the wave. It is assumed that k is a complex wave number and both parts, real and imaginary,

$$k = k' + ik''$$

depend on three material parameters (ε, μ, δ) and the frequency of the electromagnetic waves.

Very often the permittivity ε_{wz} is described as a relative value: the actual permittivity as a ratio with the permittivity of a vacuum, which has a value of $\varepsilon_0 = 8,85 \cdot 10^{-12} \text{ Fm}$. Similarly μ_{wzg} is the ratio of magnetic susceptibility to the susceptibility of a vacuum, which has a value of $4,5 \cdot 10^{-7} \text{ Hm}^{-1}$.

Generally both components of wave number are dependant on the dielectric loss angle.

$$\Delta = \frac{\sigma}{\mu\omega}$$

such that

$$k^2 = \omega^2 \varepsilon \mu + i \omega \mu \sigma$$

and

$$k' = \omega \sqrt{\frac{\mu\varepsilon}{2} \left(\sqrt{1 + \operatorname{tg}^2 \Delta} + 1 \right)}$$

$$k'' = \omega \sqrt{\frac{\mu\varepsilon}{2} \left(\sqrt{1 + \operatorname{tg}^2 \Delta} - 1 \right)}$$

The real part of the complex wave number k is connected with the phase velocity by the relationship

$$C = \frac{\omega}{k'} = \frac{\frac{2\pi}{T}}{\frac{2\pi}{\lambda}} = \lambda \cdot \nu$$

The imaginary part describes the attenuation.

Generally:

$$k = \frac{\omega}{C} + i\alpha$$

It may be shown that (A n n a n 1996) (Fig. 3) the way the intensity the coefficients k' and k'' change with ω depends on the ratio of the displacement electrical current and the conduction of electrical current.

Parameter

$$\omega_T = \frac{\sigma}{\varepsilon}$$

is taken into consideration. For a value of ω less then ω_s both parameters k' and k'' , it depends on $\sqrt{\omega}$, and when ω greater than ω_s this values of phase velocity v_∞ and attenuation α_∞ have form:

$$v_\infty = \frac{1}{\sqrt{\varepsilon\mu}} = \alpha_\infty = \frac{1}{2} \sqrt{\frac{\mu}{\varepsilon}} \sigma$$

The values for ω_T divide whole frequency intervals ω in which the geo-radar are recorded on two parts. These signals which are recorded at a frequency less than ω_c have dissipation and attenuation depending on frequency. If the signals were sent at a frequency interval less than ω_T with a characteristic $S_A(t)$ then, after transmission over distance r it is described by the function

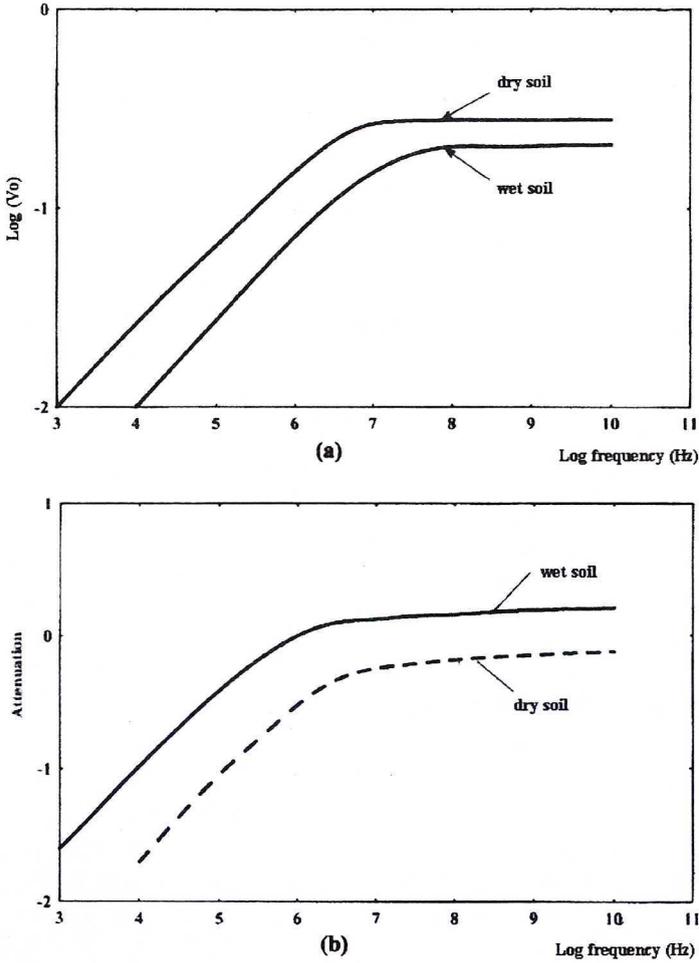


Fig. 3. Phase velocity: (a) and attenuation (b) changes with frequency for dry and wet soil (Annan 1996)

$$f_A(t) = S_A(t) * \left[\frac{\Gamma r}{2\sqrt{\pi t^3}} e^{-\frac{\Gamma^2 r^2}{4t}} \right]$$

Where $\Gamma = \sqrt{\mu\sigma}$

For signals recorded at a frequency interval higher that ω_T with a characteristic $S_B(t)$ the signal at the r distance have the form

$$f_B(t) = \frac{S_B\left(t - \frac{r}{V_\infty}\right)}{r} e^{-\alpha r}$$

For frequencies above ω_T the attenuation of the waves depends on σ and is independent of ω . It can be shown that the frequency border ω_T for a medium with

permittivity 10 and resistivity about $100 \Omega\text{m}$ is near to 120 MHz and lies within the frequency range used for geo-radar measurement.

Dispersion in the radar signals is observed and for greater distances of penetration changes in their properties occur. It must also be mentioned that geo-radar dispersion is not solely caused by changes in the transmission parameters, but may be caused by activation of additional dielectric mechanisms, such as bond particle relaxation (Keller, 1987, Olhoeft, 1987).

In media without dispersion for frequencies over ω_c the following phenomena occur.

- Attenuation of waves due to the electrical resistivity of the medium and scattering and dissipation of waves due to geometrical spreading of the geo-radar energy.

- Scattering due to reflection from small inhomogeneities.

- Scattering due to reflection from layer boundaries and large inhomogeneities.

It should be stressed that the first factor markedly limits the depth of geo-radar wave penetration and the information obtainable about underlying structures.

Assuming that the recording devices have a dynamic range of about 80 Db, the following depths can be reached using geo-radar equipment. (σ — electrical conductivity, H — depth of penetration)

σ [S/m]	H [m]
0.025	1.4
0.010	3.0
0.005	near.6.0
0.01	near.25.0

4. The influence of contamination migration and intensity of diffusion on the dielectric properties of soil

The way in which soil is contaminated with hydrocarbon materials depends on several factors.

- The type of soil.
- The water-level in the soil.
- The way the grains of the soil are wetted.
- The type of contamination (i.e. chemical structure).
- The time that has elapsed since the contamination began.

If the source of the contamination is a cracked pipe or a leaking storage tank the contamination will tend to be concentrated. If the contamination has flowed as the result of a hydraulic gradient the model is changed and the hydrocarbons will form a layer spread over the water table.

The second model is particularly interesting, as it is connected with the spread of contamination in soil and the increased risk of changes in the hydro-geological environment due the migration of hydrocarbons.

Very often such flow takes place in quaternary geological structures in which the hydraulic permeability varies very considerably.

If the rock mass is homogenous then the flow velocity \vec{V} , measured by the i -th component of the liquid flowing in unit time through a unit surface perpendicular to the direction of flow may be written according to Darcy's formula

$$\vec{V}_i = \frac{K_i}{\mu_i} (\nabla p + g \Delta \rho \vec{z} + \nabla p_c) = \frac{K_i}{\mu_i} \nabla M$$

where V_i — filtration velocity for the i -th component of the liquid flowing through a porous medium (as defined above) K_i — the permeability for the i -th component, μ_i — the kinetic viscosity of the i -th component of the liquid g — acceleration due to gravity, $\Delta \rho$ — the difference in density between water and the contaminating substance, ∇p — the pressure gradient, ∇p_c — the capillary pressure gradient. It is possible to construct the relative permeability of the two liquid materials (K_r — hydrocarbons, K_w — water)

$$K_r = \frac{K'_1}{K} \quad \text{i} \quad K_w = \frac{K'_2}{K}$$

where K'_1 — permeability of water, K'_2 — permeability of hydrocarbons, K — the permeability of a mixture.

The relative permeability of each component depends on the level of saturation. The changes in permeability caused by the level of saturation are very pronounced — see Fig. 4.

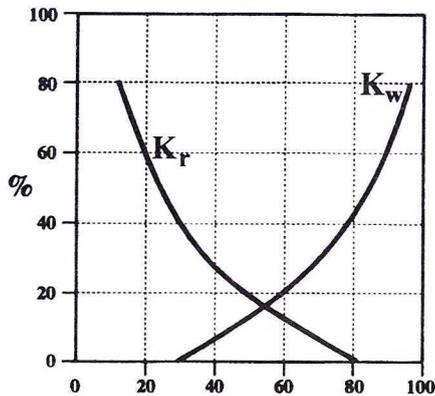


Fig. 4. Changes of relative permeability of water (K_w) and hydrocarbons (K_r) in a porous medium in different saturation conditions

For media with a large vertical differentiation of hydraulic properties the flow-patterns of mixtures of water and hydrocarbons are particularly complicated.

Based on Darcy's law, and assuming a condition of stationary flow to be

$$\Delta V_i = 0$$

where Δ — Laplace's operator.

Assuming that capillary pressure may be approximated using the formula

$$p_c = \frac{1}{K^a} \delta \ln K$$

where δ — fluctuation of function $\ln K$ is a power related to the permeability and the mean radius of the pores r

$$K = r^{\frac{1}{a}}$$

The basic flow equation is then obtained

$$\nabla^2 M - \nabla \ln K_0 \nabla M = 0$$

If it is assumed that there is a differentiation in permeability the value of the coefficient of hydro-conductivity may be calculated —

$$k = \frac{K}{\mu}$$

which is different in three axes: k_x, k_y, k_z
and

$$k^2 = k_x^2 + k_y^2 + k_z^2$$

If it is assumed that the values occurring in flow equations can be divided on the trend part, denoted ($\langle \rangle$), and the fluctuation denoted δ . For example for M function:

$$\langle M \rangle = \langle p \rangle + \Delta qgz + \langle p_c \rangle$$

and the fluctuation variable

$$\delta M = \delta p + \delta p_c$$

With such assumption, the flow can be described on the basis of a stochastic model. This model is a mathematical expression of the assumption that the water is seeking those flow channels that incur the lowest energy losses. The resulting hydraulic gradients are variable, as also are the filtration velocities and the way in which the flow-paths are selected.

Measurements of hydraulic properties are introduced (L e r c h e, T h o m s o n 1994)

$$q_{ij} = \int d^3 k^{(w)} k_z^{2(w)} k_i^{(w)} k_j^{(w)} k^{-4(w)} r(k)$$

where $r(k)$ is the normalised spectrum of spatial permeability for water,

$$\int d^3 k r(k) = 1$$

For hydrocarbon contaminations

$$s_{ij} = \int d^3 k^{(0)} k_z^{2(0)} k_i^{(0)} k_j^{(0)} k^{-4(0)} R(k)$$

where: $R(k)$ — is the normalised spectrum of spatial permeability for contaminations. Then, the measure of local anisotropy is the “length of correlation matrix” defined as

$${}^{(w)}l_{ij} = \left(\frac{|q_{ij}|}{\int d^3 k^{(w)} k_z^2 k^{-4(w)} r(k)} \right)^{1/2}$$

$${}^{(0)}l_{ij} = \left(\frac{|s_{ij}|}{\int d^3 k^{(0)} k_z^2 k^{-4(0)} R(k)} \right)^{1/2}$$

As described, the variability of hydraulic conductivity exerts an intense influence on the hydraulic gradients. With vertical flow, assuming the hydro-conductivity coefficient at the surface $z = 0$ is $K_*(0)$, and hydraulic gradient $f(0)$ are related to this values on the depth z

$$f_{*z}(0)k_*(0) = f_{*z}(z)k_*(z)$$

Spatial fluctuations may change these parameters (L e r c h e, T h o m s o n, 1994). The following parameters, important for liquid flow, can now be established.

A) Gradient of hydraulic pressure for

a) Water

b) Hydrocarbon contamination

$$f(z) = f_*(z) \left[\frac{f_*(z)}{f_*(0)} \right]^{-n}$$

$$G(z) = G_*(z) \left[\frac{G_*(z)}{G_*(0)} \right]^{-m}$$

$$n = \delta_w^2 \int d^3 k^{(w)} k_z^2 k^{-2(w)} r(k)$$

$$m = \delta_0^2 \int d^3 k^{(0)} k_z^2 k^{-2(0)} R(k)$$

$$\delta_w^2 = \langle (\delta \ln k^{(w)}(x))^2 \rangle$$

$$\delta_0^2 = \langle (\delta \ln k^{(0)}(x))^2 \rangle$$

where $k^{(i)}$ — hydraulic conductivity for $i = w$ — water, $i = 0$ — contamination, ρ — density, μ — viscosity, δ — variance in log-normal description of permeability, which often approximates to the real changes of permeability created by the lithological structure. f_* and G_* being the pressure-gradient in a medium in which there is no spatial fluctuation of permeability.

B) Flow velocity.

For water

$$V_w = V_{n*} \left[\frac{f_*(z)}{f_*(0)} \right]^{-n} \left(1 + n + \frac{1}{2} \delta_w^2 \right)$$

where V_{n*} — the water flow velocity in a medium without fluctuations of permeability.

For hydrocarbon contaminants

$$V_0 = V_{0*} \left[\frac{G_*(z)}{G_*(0)} \right]^{-m} \left(1 + m + \frac{1}{2} \delta_0^2 \right)$$

where V_{0*} — the contamination flow velocity in a medium without fluctuations of permeability and the ratio of the water and hydrocarbon flow velocities.

$$\left[\frac{V_0^{(0)}/V_w^{(0)}}{V_{0*}/V_{w*}} \right] = \frac{\left[\frac{{}^{(0)}k(z)}{{}^{(0)}k(0)} \right]^m}{\left[\frac{{}^{(w)}k(z)}{{}^{(w)}k(0)} \right]^{-n}} \left(1 + m + \frac{1}{2} \delta_0^2 \right) \left(1 + n + \frac{1}{2} \delta_w^2 \right)^{-1}$$

C) The ratio of variants for the vertical components for water and contamination.

$$\frac{\langle \delta v_z^2 \rangle}{\langle \delta w_z^2 \rangle} = R_{0w} (s_{ss} + s_{yy}) / (q_{xx} + q_{yy})$$

where $\langle \rangle$ is the mean value.

D) The ratio of the horizontal components of water/hydrocarbon flow velocities may be written

$$\frac{\langle \delta v_i \delta v_j \rangle}{\langle \delta w_i \delta w_j \rangle} = R_{0w} \frac{s_{ij}}{q_{ij}}$$

where

$$R_{0w} = \left(\frac{\delta_0}{\delta_w} \right)^2 \exp(\delta_0^2 - \delta_w^2) \left(\frac{V_{0*}}{V_{w*}} \right)^2 \left[\frac{k_0(z)}{k_0(0)} \right]^{m+1} \left[\frac{k_w(z)}{k_w(0)} \right]^{-(n+1)}$$

These considerations prove that variability in hydraulic conductivity modifies the flow characteristics. Variability of hydraulic gradients causes variations in flow velocities. Both variations result from the lithological structure of the medium. The distribution of the contamination and its variable diffusion in the medium results from changes in permeability.

Several other factors influence the permeability, such as:

A) Sandiness.

It should be mentioned that the permeability of quarternary deposits varies very considerably between sand and shales.

For example it is equal for;

sands 1000—100 md.
shales 10^{-6} — 10^{-9} md.

This means that permeability may vary between 10^4 and 10^{-6} .

It may be written

$$K = K_{sh}^{1-s} K_s^s$$

where s — sandiness, K_{sh} — permeability of deposit of shales, K_s — permeability of sand. The sandiness coefficient has the form

$$A(z) = \ln \frac{K_s}{K_{sh}}$$

And the mean value of $\ln K$ may be written

$$\langle \ln K \rangle = \ln K_{sh} + \langle s \rangle \Lambda(z)$$

B) Ground humidity.

If the relative permeability is dependant on the ground humidity (w — coefficient of humidity)

$$\frac{K_0}{K_w} = q^{1-w} r^w$$

where K_0 — permeability of contamination, K_w — permeability of water.
For 100% water humidity ($w = 1$)

$$K_0 = K_w r$$

for 100% contamination wetting ($w = 0$)

$$K_0 = K_w q$$

then

$$\langle \ln K_0 \rangle = \langle \ln K_w \rangle + \langle q \rangle + \langle w \ln r/q \rangle$$

C) Surface tension.

Taking consideration of surface tension τ then

$$p_c = c \tau c \cos \alpha \left(\frac{1}{r_{\max}} - \frac{1}{r_{\min}} \right)$$

where p_c — capillary pressure, r_{\max} , r_{\min} — the variance in pore sizes, c — a constant,
 α — angle of wetting

If,

$$K \approx r^{1/a}$$

Then

$$p_c \approx \left(\frac{1}{K_{\max}^a} - \frac{1}{K_{\min}^a} \right)$$

If

$$K_{\max} = K_{\min} + \delta K$$

Then

$$dp_c = \frac{\delta K_c}{K^{a+1}} \approx \frac{1}{K^a \delta \ln K}$$

The flow velocity in a porous medium according to Darcy's Law

$$\frac{d\zeta_0}{dt} = -\frac{K_0}{\mu_0} \cdot \frac{1}{K^a} q \ln k$$

where ζ_0 expresses the movement of elements from a medium of low permeability to a medium of high permeability, μ_0 — the viscosity.

Thus the flow of water and hydrocarbon contaminations in media with varying levels of permeability is complicated.

Nevertheless, it is possible to establish some properties of the flow. The hydrocarbons are pushed out by the water and by buoyancy. It should be stressed that the relative permeability of the two substances differs markedly.

In the presence of water capillary pressure, hydrocarbons are washed out of shales and fine sands to sands with a large-grain structure. For flows with a horizontal component a concentration component, C is introduced, which is a measure of the ability of a sand body to concentrate and retain hydrocarbon pollution within itself, related to the quantities of liquids in the surrounding structures.

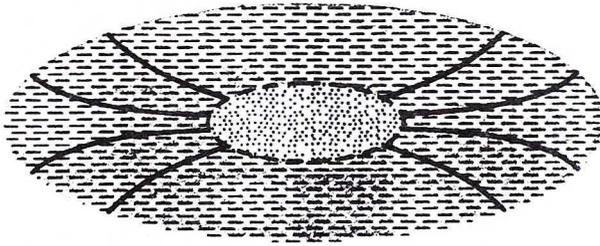


Fig. 5. The distribution of flow lines of contamination in the locality of a sand body

Differences in hydrocarbon and water concentration densities cause more intensive movements of the former rather than the latter. This results in a concentration of hydrocarbons above the water-table and in their movement as a result of alterations of the latter (eg. by rainfall).

Changes in the lithology, both vertically and horizontally, creates accumulations of hydrocarbons, contained within localised hydraulic barriers and their gradual disappearance.

In conclusion, the following outcomes are worthy of emphasis:

- In observed practical examples pollution tends to be concentrated above the water-table.
- Configurations of hydrocarbon plumes are complex, due to variance in the lithological structures and the hydraulic gradients which exist near to the ground surface in the soils, for the most part consisting of sands, clays and shales.
- The changes in lithological structures are also significantly affected by depth and the conditions of formation of the sedimentation. In certain circumstances, a concentration of contaminants is to be expected in coarse sands — so-called 'sand bodies' in which the water is squeezed out and replaced by an inflow of hydrocarbons.
- Flow velocities in different zones can differ greatly, creating tongues of contamination, which may be transported rapidly in particular directions.

5. Geo-radar signals in ground contaminated with hydrocarbons

With regard to the discussion above, it is to be inferred that a change in the permittivity of contaminated ground is to be expected. This affects geo-radar parameters as follows:

1. Wave velocity

$$v = \frac{1}{\sqrt{\mu\epsilon}}$$

recordable on geo-radar traces.

2. Electrical conductivity. Waves in contaminated ground are less attenuated.
3. The refraction coefficient on stratigraphic boundaries

$$\Gamma = \frac{\eta_c - \eta_0}{\eta_c + \eta_0}$$

where

$$\eta_c = \sqrt{\frac{\mu}{\epsilon_c}}$$

η_c — the impedency coefficient at the lithological boundary when η_0 is the coefficient for a vacuum.

The coefficient Γ depends on the differentiation of dielectric properties at the stratigraphic boundaries. Finally, in a relatively homogenous medium where a contamination zone appears over the water table and in result of the water column stresses smoothing of the hydrological table may be expected. Because the geo-radar signals involve an estimation of the wave energy reflected from such surfaces it may be inferred that an increase in signal frequency can result from reflections from the surface of the contaminated layer. If such signals are reflected from different surfaces (Fig. 6),

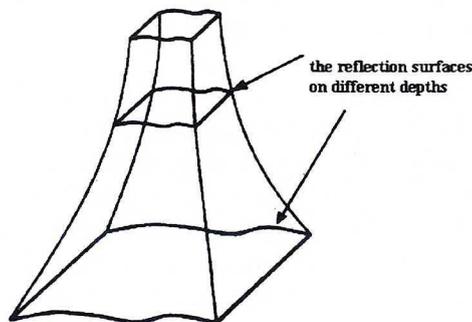


Fig. 6. Dependence of geo-radar signal structure on the character of the reflective surface

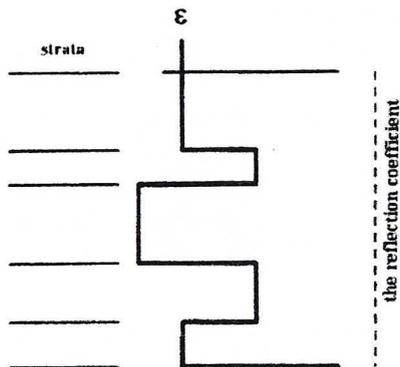


Fig. 7. Dependence of signal structure on variances in permittivity

due to the existence of conductive and non-conductive hydrological structures, the signal structure and its spectrum is complex. If some areas of the geological cross-section are contaminated with hydrocarbons according to the mechanism described above changes to the signals and spectra are to be expected.

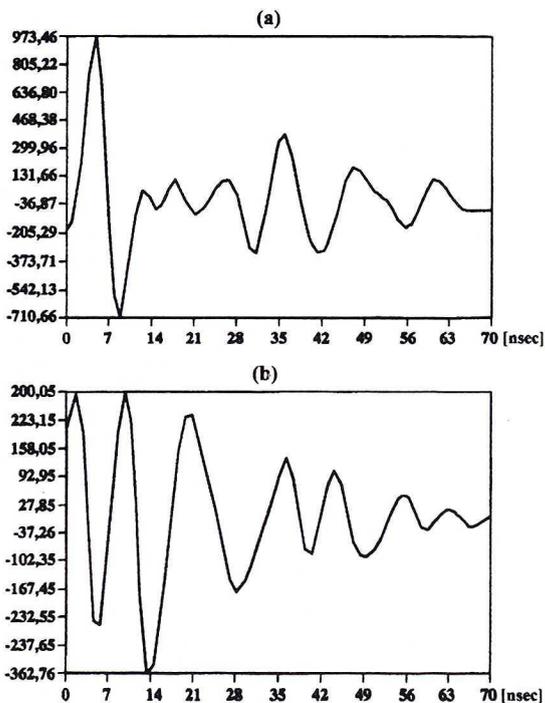


Fig. 8. Geo-radar measurements obtained in former Soviet military base "Krzywa". Averaged trace from 15 adjacent traces: (a) clean zone, (b) contaminated zone

Geo-radar measurements were carried out in the area of the former Soviet military base "Krzywa". Recordings made in clean and contaminated areas were averaged by adding 15 adjacent traces. As a further consideration signals were analyzed at chosen time-intervals with regard to the depth of the water-table in control bores. The time windows were 70 ns. These are shown on Fig. 8.

The interference of the signals may explain the changes in spectra created in clean and contaminated areas. In contaminated areas the strongly reflective layer disappears, and the signal itself is markedly weaker.

6. Final conclusions

It would seem that a unique interpretation of geo-radar readings on contaminated ground is not possible. The following points should be noted.

The rapid decrease of geo-radar energy with depth, together with reduced resolution.

The flow of contamination in a medium with hydraulic variability is complex.

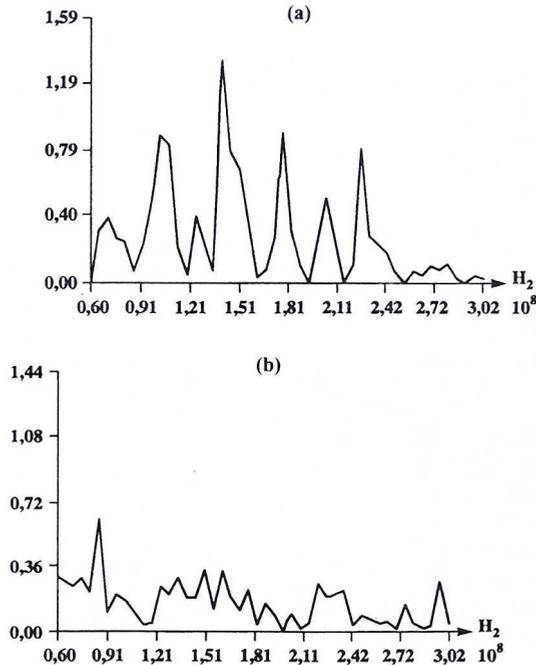


Fig. 9. The spectra of geo-radar signals; (a) signals from contaminated area, (b) signals from clean area

There is a relationship between the physical properties of the rock-medium — particularly the dielectric properties, and the structure of contaminated soil.

This results in very clear, but not unique, observable features associated with contaminated areas, in particular changes in permittivity and electrical conductivity, which would seem to indicate that geo-radar methods might be useful in locating such areas.

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