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Seismoelectric Effect Associated with Rayleigh Wave Propagation

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Abstract—In the scope of Frenkel's equation, an analytical solution is obtained for pore pressure and electrokinetically induced electric field caused by the Rayleigh surface wave propagation in a poroelastic fluid-saturated medium. The problem is solved in the frequency domain with the allowance for the boundary condition on the Earth's surface. It is shown that the solution can be represented in the form of a sum of two waves, the first prevailing in the near-surface layer and rapidly decaying with depth, and the second covering a much greater depth interval and associated with longitudinal component of the Rayleigh wave. The rate of exponential decay of the first wave with depth is determined by the skin depth which, in turn, depends on the permeability coefficient of a poroelastic medium and on a number of other parameters. As a result, vertical component of the electric field associated with the first wave is highly sensitive to the change in the permeability of the surface layer, which opens the possibility of its determination from the observed seismoelectric signal. The first wave creates the dominant part of the electrokinetic effect on the surface. In accordance with the Helmholtz-Smoluchowski equation, we derived the expressions for the vertical and horizontal components of the electric field strength. Based on the estimated parameters of the Rayleigh wave recorded in the region of Mt. Wrangell, Alaska after the $M = 9.0$ Sumatran 2004 earthquake, the expected amplitudes of the vertical component of the coseismic electric field are found to range between dozens of μV/m and tenths to units of V/m. It is shown that the amplitudes and the skin depth for this component substantially depend on the permeability coefficient of the medium.

Keywords: Biot theory, Frenkel equation, porous fluid-saturated medium, earthquakes, Rayleigh wave, electric field, electrokinetic effect

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INTRODUCTION

The study of seismoelectric (SE) phenomena in geophysics began in the first half of the 20th century from the works of R.R. Thompson, A.G. Ivanov, Ya.I. Frenkel, and M. Biot (Thompson, 1936; Ivanov, 1939; 1940; Frenkel, 1944; Biot, 1956). In these works, the electrokinetic (EC) phenomenon was described in the context of the Helmholtz–Smoluchowski equation linking the electric field strength with the pore pressure gradient, and the corresponding theory based on the fluid dynamics of porous media under seismic impact was proposed.

Although interest in the SE method has increased in recent decades (Pride, 1994; Potapov et al., 1995; Svetov, 2008; 2015; Revil and Jardani, 2010; Revil et al., 2015; Jouniaux, 2016; Alekseev and Gokhberg, 2018; 2019), the studies were mainly related to the relatively high frequency processes—the Biot waves. Modeling and interpretation of the SE signals require solving a complex self-consistent problem which combines fluid dynamics equations and electromagnetic (EM) field equations. Moreover, the analytical solution of the latter was obtained in a very limited set of cases (Pride, 1994), which is insufficient for the comprehensive assessment of the information capabilities of the SE method. It seems that the representations of extraneous external current in the form of some frequency dependences including pressure gradient or displacement difference between solid and liquid phases, which were proposed by some authors (C. Pride, B.S. Svetov and V.P. Gubatenko), will allow modeling the SE fields but need numerical methods to solve the filtration problem. The problem of the numerical analysis of pore pressure distributions in the Biot's poroelastic model and its generalizations has been addressed in many publications but, as a rule, without consideration of the specificity of a particular deformation process.

In the practice, the corresponding methods are used to a very limited extent because of facing difficul-

† Deceased.

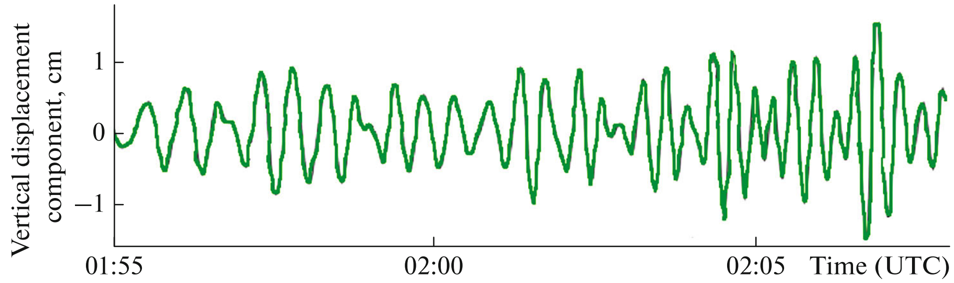

Fig. 1. Fragment of low-frequency (0.01–0.1 Hz) component of vertical oscillations recorded at WANC station (USA, Alaska, Mt. Wrangell), corresponding to teleseismic signal from Sumatran earthquake of December 26, 2004 (from (West et al., 2005), modified).

ties in recording and interpretation of seismoelectric fields. At the same time, it is understood that with introducing the technologies based on the use of seismoelectric signals, the spectrum of the obtained information about the structure, parameters, and dynamic state of the subsurface can be significantly expanded (Svetov, 2015; Revil et al.).

In this work, we theoretically analyze the propagation of the Rayleigh waves and the related pore pressure fluctuations within the Biot model of a fluid-saturated poroelastic medium. Using teleseismic signals recorded in the region of Mt Wrangel, Alaska, after the Sumatran earthquake ($M = 9.0$, 2004), we determine the parameters of deformation of the medium based on which we subsequently estimate the amplitude of pore pressure variations. We present the analytical solution of the Frenkel's equation, discuss its characteristic features, and analyze the behavior of the electric field arising under the action of the pore pressure gradient in the scope of electrokinetic mechanism.

Based on the considered theoretical model, the method can be proposed to estimate a number of elastic and petrophysical parameters by measuring the electric field related to the pore pressure gradient caused by the passage of surface seismic waves.

ESTIMATING THE DEFORMATION PARAMETERS OF THE MEDIUM BASED ON THE RECORD OF A TELESEISMIC SIGNAL

To determine the characteristic parameters of the Rayleigh wave, we consider the records of teleseismic signal detected in Alaska after the strongest Sumatran earthquake ($M = 9.0$, 2004) (Fig. 1). According to the data presented in (West et al., 2005), the Rayleigh wave velocity $U = 3.7$ km/s, oscillation period $T = 30$ s, and wavelength $\lambda = UT = 111$ km.

To analyze the displacement field, we use the formulas following from the wave equation in the case of a plane Rayleigh surface wave propagating in the xz-plane along the free surface of the half-space $z \le 0$ in the x-axis direction (Landau and Lifshitz, 1965):

$$\begin{aligned} u_x &= u_{tx} + u_{\ell x} \\ &= b\left[\frac{a}{b}\frac{\chi_t}{k}\exp(\chi_t z) + \exp(\chi_\ell z)\right]\exp[i(kx - \omega t)], \end{aligned} \tag{1}$$

$$\begin{aligned} u_z &= u_{tz} + u_{\ell z} \\ &= -ib\left[\frac{a}{b}\exp(\chi_t z) + \frac{\chi_\ell}{k}\exp(\chi_\ell z)\right]\exp[i(kx - \omega t)]. \end{aligned} \tag{2}$$

Here, u_x and u_z are the displacement field components; u_ℓ and u_t are the longitudinal and transverse displacement components propagating with velocities c_ℓ and c_t and having amplitudes b and a, respectively; and k is the wavenumber. The attenuation coefficients χ_l and χ_t are connected with wave number k, frequency ω and velocities c_ℓ and c_t by the following relations:

$$\begin{aligned} \chi_l^2 &= k^2 - \frac{\omega^2}{c_l^2} = k^2(1 - \xi^2\gamma), \\ \chi_t^2 &= k^2 - \frac{\omega^2}{c_t^2} = k^2(1 - \xi^2). \end{aligned} \tag{3}$$

Here, $\gamma = \dfrac{c_t^2}{c_l^2} = \dfrac{1 - 2\sigma}{2(1 - \sigma)}$. Parameter $\xi = \omega/(c_t k)$ is determined by the algebraic equation

$$\xi^6 - 8\xi^4 + 8\xi^2(3 - 2\gamma) - 16(1 - \gamma) = 0. \tag{4}$$

Leibenzon (1947) presented the exact solution of this equation for the Poisson ratio $\sigma = 0.25$:

$$\xi^2 = 2 - \frac{2}{\sqrt{3}} = 0.8453. \tag{5}$$

Following West et al. (2005), we use this ξ^2 value. We obtain

$$\chi_l = 0.8475k, \quad \chi_t = 0.3933k. \tag{6}$$

Since $k = 2\pi/\lambda = 5.661 \times 10^{-5}\ \text{m}^{-1}$, then

$$\chi_l = 4.797 \times 10^{-5}\ \text{m}^{-1}, \quad \kappa_t = 2.226 \times 10^{-5}\ \text{m}^{-1}. \tag{7}$$

Hence, the characteristic attenuation lengths of the longitudinal and transverse components of the Rayleigh wave are estimated at

$$L_l = \frac{1}{\chi_l} = 20.8 \text{ km}, \quad L_t = \frac{1}{\chi_t} = 44.9 \text{ km}. \tag{8}$$

This means that the wave propagates in the crustal surface layer with a thickness of 20–45 km.

The amplitude ratio $\frac{a}{b}$ of the transverse and longitudinal components is determined by the formula (Landau and Lifshitz, 1965):

$$\frac{a}{b} = -\frac{2-\xi^2}{2\sqrt{1-\xi^2}}.$$

The substitution of the ξ^2 value according to (5) yields

$$\frac{a}{b} = -1.468. \tag{9}$$

The amplitude of the Rayleigh wave vertical component on the surface $z = 0$ according to (2) is

$$u_z = -ib\left(\frac{\chi_l}{k} + \frac{a}{b}\right)\exp i(kx - \omega t). \tag{10}$$

Substituting here the above χ_ℓ/k and a/b, values we arrive at

$$u_z = ib \times 0.6205 \exp i(kx - \omega t). \tag{11}$$

According to (West et al., 2005), the vertical trough-to-peak ground displacements reached 1.5 cm. Correspondingly, the maximum amplitude of vertical displacements was 0.75 cm. Equating this value to the amplitude u_z, we find parameter b:

$$b = 1.2087 \text{ cm}. \tag{12}$$

VOLUMETRIC DEFORMATIONS IN THE RAYLEIGH WAVE AND THE FRENKEL'S EQUATION

The electrokinetic effect associated with the propagation of a Rayleigh wave in a porous fluid-saturated medium can be described in the scope of the Frenkel's equation (Frenkel, 1958) for pore pressure perturbations p. Parameter p has the meaning of hydrodynamic pressure arising in the pores of a fluid-saturated rock under the action of external mechanical forces. In the case of low-frequency processes including teleseismic oscillations with periods of tens of seconds, the Frenkel's equation can be reduced to the following form (Gokhberg et al., 2009):

$$\Delta p - \frac{\beta'\eta}{k_\text{p} K_l}\frac{\partial p}{\partial t} = \frac{\beta\eta}{k_\text{p}}\frac{\partial\vartheta}{\partial t}, \tag{13}$$

where ϑ is the volumetric strain (dilatation) of the medium; ρ and η are density and fluid viscosity; and k_p is the permeability coefficient.

$$\beta = \left(1 - \frac{K}{K_S}\right)\frac{1}{n}, \quad \beta' = 1 + (\beta - 1)\frac{K_l}{K_S}. \tag{14}$$

Here, n is the porosity coefficient; K, K_l and K_S are the bulk moduli of a dry porous rock, pore liquid, and a solid material composing the rock matrix, respectively.

By definition, $\vartheta = \mathrm{div}\mathbf{u}$. Substituting components (1) and (2) of the displacement vector $\mathbf{u}$ in this formula, we find

$$\vartheta = ibk\left[1 - \left(\frac{\chi_\ell}{k}\right)^2\right]\exp(\chi_\ell z)\exp[i(kx - \omega t)]. \tag{15}$$

From this expression it can be seen that volumetric strain is only related to the longitudinal component of the Rayleigh wave just as it should be, since for the transversal component $\mathrm{div}\mathbf{u}_t = 0$.

Introducing the parameters

$$d = \frac{\beta'\eta}{k_\text{p} K_\ell}, \quad q = \frac{\beta\eta}{k_\text{p}}, \quad \vartheta_0 = bk\left[1 - \left(\frac{\chi_\ell}{k}\right)^2\right] \tag{16}$$

and rewriting Eq. (13), we obtain

$$\Delta p - d\frac{\partial p}{\partial t} = -iq\vartheta_0\omega\exp(ik + \chi_\ell z - i\omega t). \tag{17}$$

Let us estimate parameters d, q, ϑ. For doing so, we assume the known characteristics of the medium: water viscosity $\eta = 0.82 \times 10^{-3}$ Pa s at 20°C, water bulk modulus $K_l = 2.1 \times 10^9$ Pa (*Fizicheskie*..., 1991), permeability coefficient $k_p \sim 10^{-8}/10^{-10}/10^{-12}/10^{-14}/10^{-16}$ m^2 (Schon, 2011). To estimate quantities β and β', we use the ratios of mechanical parameters of water saturated rock $K/K_s \approx 0.5$, $K_l/K_s = 0.1$ (Gershenson and Bambakidis, 2001), which yields $\beta = 5$, $\beta' = 1.4$. For the case $k_p = 10^{-12}$ m^2 (permeable carbonates), based on formulas (14), (16) and the above reference data, we obtain the following estimates: $d = 5.467 \times 10^2$ m^{-2} s, $q = 4.1 \times 10^{12}$ Pa m^{-2} s. Parameter ϑ is determined from the above estimates based on the record of the Rayleigh wave: $\vartheta_0 = 1.9278 \times 10^{-7}$.

Let us find the solution to Eq. (17) in the following form:

$$p(x,z,t) = A(z)\exp(ikx + \chi_\ell z - i\omega t). \tag{18}$$

Substituting (18) in (17), we obtain the following equation for function $A(z)$:

$$\begin{aligned} A''(z) + 2\chi_\ell A'(z) + [(\chi_\ell^2 - k^2) + id\omega]A(z) \\ = -iq\vartheta_0\omega. \end{aligned} \tag{19}$$

This equation has a particular solution in the form of a constant:

$$A^{(0)}(z) = -\frac{iq\vartheta_0\omega}{id\omega + \chi_\ell^2 - k^2} \cong -q\vartheta_0/d = \text{const}, \quad (20)$$

which allows us to pass to the homogeneous equation

$$A''(z) + 2\chi_\ell A'(z) + [\chi_\ell^2 - k^2 + id\omega]A(z) = 0. \quad (21)$$

We search for the solution of this equation in the form

$$A(z) = A_0 \exp(\kappa z). \quad (22)$$

Substituting (22) in (21), we arrive at the algebraic equation

$$\kappa^2 + 2\chi_{\ell\ell}\kappa + \chi_\ell^2 - k^2 + id\omega = 0, \quad (23)$$

which can be recast in the form

$$(\kappa + \chi_\ell)^2 = -id\omega + k^2. \quad (24)$$

The value of quantity $d\omega$ in the right-hand side of this equation is by 11 orders of magnitude greater than k^2, therefore we may highly accurately accept

$$\kappa \cong -\chi_\ell \pm \sqrt{-i}\sqrt{d\omega} = -\chi_\ell \pm \frac{-1+i}{\sqrt{2}}\sqrt{d\omega}.$$

From the two solutions we select the one corresponding to the attenuation with depth, which yields

$$\kappa = -\chi_\ell + \frac{1-i}{\delta}, \quad (25)$$

where

$$\delta = \sqrt{\frac{2}{d\omega}} = \sqrt{\frac{2k_p K_\ell}{\omega\eta\beta'}}. \quad (26)$$

Hence, the solution of the homogeneous equation (21) is

$$A(z) = A_0 \exp\left(-\chi_\ell z + \frac{1}{\beta}z - i\frac{1}{\beta}z\right).$$

Together with the particular solution (20), we obtain the solution of the heterogeneous equation (19):

$$A(z) = A_0 \exp\left(-\chi_\ell z + \frac{1}{\beta}z - i\frac{1}{\beta}z\right) - q\vartheta_0/d, \quad (27)$$

and, in correspondence with (18), the solution of Eq. (17) determining the dynamics of the pore fluid:

$$p = \left[A_0 \exp\left(-\chi_\ell z + (1-i)\frac{1}{\beta}z\right) - \frac{q\vartheta_0}{d}\right] \times \exp(ikx + \chi_\ell z - i\omega t). \quad (28)$$

On the free surface, the following condition should be satisfied:

$$z = 0, \quad p = 0. \quad (29)$$

This condition determines the constant $A_0 = q\vartheta/d$. Thus, the resulting solution of Frenkel's equation is

$$p = \frac{q\vartheta_0}{d}\exp\left(i(kx - \omega t) + \frac{1-i}{\delta}z\right) - \frac{q\vartheta_0}{d}\exp(ikx + \chi_\ell z - i\omega t). \quad (30)$$

In the real variables, the solution has the following form:

$$p = \frac{q\vartheta_0}{d}e^{z/\delta}\cos(kx - z/\delta - \omega t) - \frac{q\vartheta_0}{d}e^{\chi_\ell z}\cos(kx - \omega t). \quad (31)$$

The obtained solution contains two wave components. The wave

$$p_2 = -\frac{q\vartheta_0}{d}e^{\chi_\ell z}\cos(kx - \omega t) \quad (32)$$

is associated with the propagation of longitudinal components of the Rayleigh wave. Wave

$$p_1 = \frac{q\vartheta_0}{d}e^{z/\delta}\cos(kx - z/\delta - \omega t) \quad (33)$$

propagates in the surface layer having a thickness on the order of δ and accompanies the Rayleigh wave. The p_1 wave creates dominant part of the electrokinetic effect. Figure 2 shows the graphs of the amplitude of pore pressure fluctuations for components p_1 and p_2 in a medium with the above parameters depending on the depth.

ELECTROKINETIC EFFECT

The electric field strength in the electrokinetic effect is determined by the formula

$$\mathbf{E} = C\nabla p. \quad (34)$$

Here, C is the local coefficient of the streaming potential. According to (Surkov, 2000), for various sandstones and porous rocks $C \approx (4-5)\times 10^{-6}$ V/Pa. The electric field has two components—horizontal E_x and vertical E_z:

$$E_x = C\frac{q\vartheta_0}{d}k\left[\exp(z/\delta)\sin(kx - z/\delta - \omega t) - \exp(\chi_\ell z)\sin(kx - \omega t)\right], \quad (35)$$

$$E_z = -C\frac{q\vartheta_0}{d\delta}\left[\sqrt{2}\exp(z/\delta)\sin(kx - z/\delta - \omega t) + \delta\chi_\ell \exp(\chi_\ell z)\cos(kx - \omega t)\right]. \quad (36)$$

The horizontal component on the surface is zero. At a depth, at $z \to -\infty$, it also goes to zero. At the same time, the vertical component behaves differently, taking on a nonzero value on the surface.

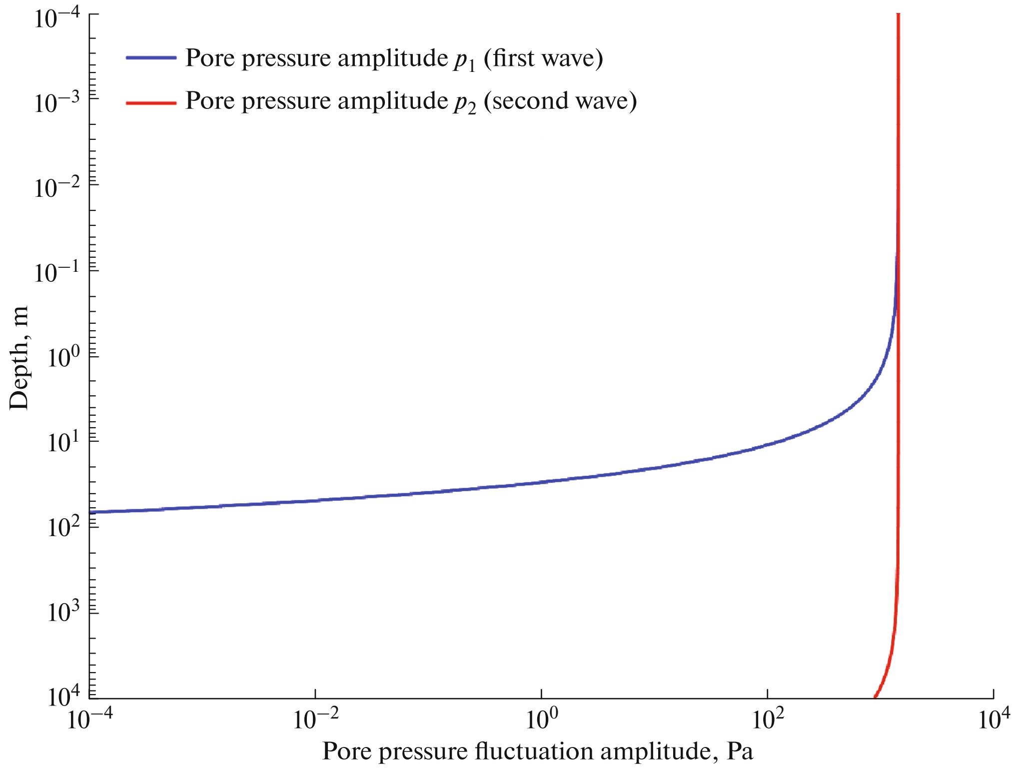

Fig. 2. Graphs of amplitudes of pore pressure first and second components within the medium, calculated by formulas (32)–(33).

In the case of the parameters of the medium selected above, $\delta \cong 0.132$ m, $\delta\chi_\ell \cong 6.33\times10^{-6} \ll 1$. From this it follows that the vertical component of the electric field strength is dominated by the contribution of the near-surface wave p_1, the maximum amplitude of the E_z component is achieved at the boundary $z = 0$. Using the above estimates of parameters q, ϑ_0, d and assuming the streaming potential to be $C = 4.5 \times 10^{-6}$ V/Pa, we can conclude that with the considered characteristic deformation induced by the arrival of the teleseismic surface wave, the expected amplitudes of the vertical component of seismoelectric signal range from tens of μV/m for highly permeable gravel-sandy water-saturated soils (permeability 10^{-8} m^2) to tenths of V/m and even first V/m in poorly permeable formations with permeability 10^{-16}–10^{-17} m^2 (Fig. 3).

Given the up-to-date possibilities of recording and processing the electric field data, these quantities can be detected fairly confidently.

As permeability decreases, the E_z amplitude in the first wave near the Earth's surface increases with the simultaneous decrease of the depth at which this field component rapidly decays. This behavior makes it possible to estimate permeability from the observed E_z amplitude, provided that other parameters of the medium are specified.

The graphs of the amplitude of the vertical and horizontal components of the electric field for the first and second waves inside the medium are shown in Fig. 3.

CONCLUSIONS

In this study, by the example of teleseismic signal recorded in Alaska after the strongest 2004 Sumatran earthquake ($M = 9.0$), the parameters of deformation of the medium accompanying the propagation of the surface Rayleigh wave are estimated, and analytical solution of Frenkel's equation which describes pore pressure fluctuations in a homogeneous fluid-saturated poroelastic medium during the propagation of this wave is obtained.

Based on the oscillation data recorded by the seismological network stations in Alaska and the estimates previously obtained by other authors for the oscillation period (~30 s) and propagation velocity (~3.7 km/s) of the Rayleigh wave (West et al., 2005), the characteristic decay length of the longitudinal and transverse components of the wave (20 and 45 km respectively), their amplitude ratio (~0.68), and displacement amplitudes (~0.7 cm for vertical component) have been calculated. Besides, formulas and estimates have been obtained for the parameters necessary for calculating volumetric strain used in the subsequent analysis when solving the fluid dynamics equation (Frenkel equation) for pore pressure perturbations. The volu-

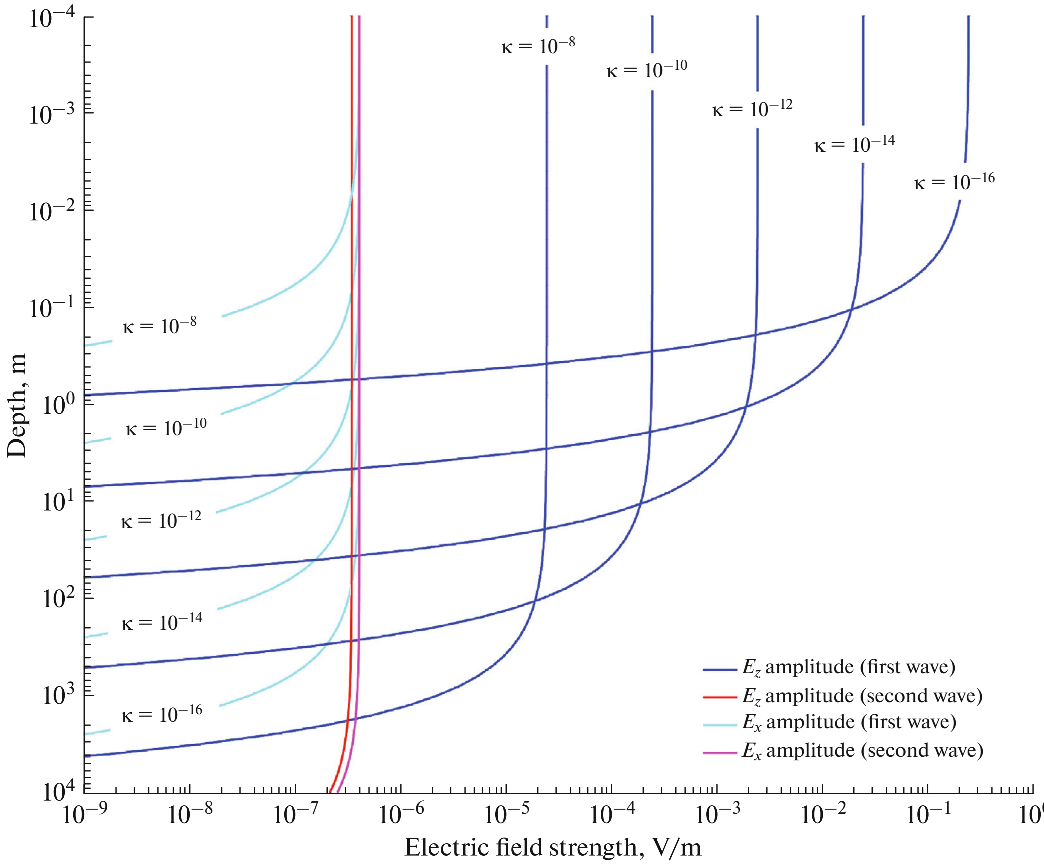

Fig. 3. Graphs of amplitudes of vertical and horizontal electric field components for first and second waves within the medium, calculated by formulas (35)–(36) with different permeability of the medium (indicated in m^2 on graphs).

metric strain amplitude estimated from these data is about 2×10^{-7}.

At the next step of the analysis, analytical solution for the pore pressure field and for the related electric field of electrokinetic origin accompanying the propagation of Rayleigh wave has been obtained in the scope of the Frenkel equation. The problem was solved in the frequency domain with boundary condition $p = 0$ on the Earth's surface. It is shown that the solution can be cast in the form of a sum of two waves: one wave dominates in the surface layer and rapidly decays with depth, and another wave covers a substantially larger depth interval and is associated with the propagation of the longitudinal component of Rayleigh wave.

The rate of exponential decay of the first wave along the depth is determined by the skin layer's thickness which depends on the permeability coefficient of a poroelastic medium and a number of other parameters. Because of this peculiarity, the vertical component of the electric field associated with the first wave is highly sensitive to a change in the permeability of the surface layer, which provides the possibility to determine it from the observed seismoelectric signal, as it was shown in the case of tidal fields (Gokhberg et al., 2007; 2009; Alekseev and Gokhberg, 2018; 2019). The first wave creates the dominant part of the electrokinetic effect on the surface of the medium. In accordance with the Helmholtz–Smoluchowski equation, the formulas for the vertical and horizontal components of the electric field strength and the estimates of these components corresponding to the Rayleigh wave parameters determined at the first step have been obtained.

The amplitude estimate of the vertical component of the electric field for the considered teleseismic signal ranges from tens of μV/m in the case of highly permeable gravel-sandy water-saturated soils (permeability 10^{-8} m^2) to tenths of V/m and even the first V/m in the case of poorly permeable formations (10^{-16}–10^{-17} m^2). At the same time, the second pore pressure component is not accompanied by such a rapid attenuation, and its gradient proves to be substantially lower, which corresponds to the characteristic amplitudes of the electrical signal on the level of a few μV/m and lower.

A very important result is the revealed dependence of not only the skin layer's thickness but also the amplitude of the vertical component of the electric field on the permeability of the medium.

Yet another implication of the obtained results is that the behavior observed in the analytical solution, which is associated with rapid decay of pressure below the earth surface, should apparently also be observed in the case of the arbitrary seismic waves propagating within a layered medium. This requires exceptionally careful meshing in the numerical simulation, with cell sizes logarithmically varying along the depth within each model layer. Otherwise, the numerical solution of the mechano-electromagnetic problem will not reflect rapid spatial changes of the pore pressure field, and the information about its dependence on the filtration parameters of the medium will be lost.

Summarizing the study, we note that the obtained analytical relations provide a fundamental possibility to determine a number of the filtration and geomechanical parameters of the near-surface layer of the medium based on the measurements of the electric field close to the surface (in shallow wells).

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

REFERENCES

Alekseev, D.A. and Gokhberg, M.B., On the possibility of estimation of the Earth crust's properties from the observations of electric field of electrokinetic origin, generated by tidal deformation within the fault zone, *Izv., Phys. Solid Earth*, 2018, vol. 54, no. 3, pp. 487–503.

Alekseev, D.A. and Gokhberg, M.B., Tidal generated electric field in the multi-layer structure and the possibilities of its employment for deriving the elastic properties and permeability of the subsurface formations, *Izv., Phys. Solid Earth*, 2019, vol. 55, no. 2, pp. 337–347.

Biot, M., General solutions of the equations of elasticity and consolidation for a porous material, *J. Appl. Mech., Trans. Am. Soc. Mech. Eng.*, 1956, vol. 78, pp. 91–96.

Fizicheskie velichiny. Spravochnik (Physical Quantities: A Reference), Grigor'ev, I.S. and Meilikhov, E.Z., Eds., Moscow: Energoatomizdat. 1991. Frenkel', Ya.I., On the theory of seismic and seismoelectric phenomena in wet soil, *Izv. Akad. Nauk SSSR, Ser. Geogr. Geofiz.*, 1944, vol. 8, no. 4, pp. 134–149.

Garagash, I.A., Gokhberg, M.B., and Kolosnitsyn, N.I., Monitoring deformation processes based on observations of vertical component of the electric field, in *Ocherki geofizicheskikh issledovanii* (Essays on Geophysical Research), Moscow: OIFZ RAN, 2003, pp. 250–256.

Garagash, I.A., Gokhberg, M.B., and Kolosnitsyn, N.I., Monitoring of deformation process by means of electric field observation, in *Mud Volcanoes, Geodynamics and Seismicity*, Martinelli, G. and Panahi, B., Eds., Dordrecht: Springer, 2005, pp. 171–179.

Gershenson, N. and Bambakidis, G., Modeling of seismo-electromagnetic phenomena, *Russ. J. Earth Sci.*, 2001, vol. 3, no. 4, pp. 247–275.

Gokhberg, M.B., Kolosnitsyn, N.I., and Nikolaev, A.I., Tidal deformations and the electrokinetic effect in a two-layer fluid-saturated porous medium, *Izv., Phys. Solid Earth*, 2007, vol. 43, no. 8, pp. 702–706.

Gokhberg, M.B., Kolosnitsyn, N.I., and Lapshin, V.M., Electrokinetic effect in the near-surface layers of the Earth, *Izv., Phys. Solid Earth*, 2009, vol. 45, no. 8, pp. 633–639.

Ivanov, A., Effect of electrization of Earth layers by elastic waves passing through them, *Dokl. Akad. Nauk SSSR*, 1939, no. 24, pp. 42–45.

Ivanov, A.G., Seismoelectric effect of the second kind, *Izv. Akad. Nauk SSSR, Ser. Geogr. Geofiz.* 1940, no. 5, pp. 600–727.

Jouniaux, L. and Zyserman, F., A review on electrokinetically induced seismo-electrics, electro-seismics, and seismo-magnetics for Earth sciences, *Solid Earth*, 2016, vol. 7, pp. 249–284.

Landau, L.D. and Lifshits, E.M., *Teoriya uprugosti, tom 7, Teoreticheskaya fizika v 10-ti tomakh* (Theory of Elasticity, vol. 7 of Theoretical Physics in 10 vols.), 3rd ed., Moscow: Nauka, 1965.

Leibenzon, L.S., *Kurs teorii uprugosti* (Elasticity Theory Course), Moscow–Leningrad: Gostekhizdat, 1947.

Naumovich, A., Efficient numerical methods for the Biot poroelasticity system in multilayered domains, *Ph. D. Thesis*, Kaiserslautern: Technische Universität Kaiserslautern, 2007.

Physical Properties of Rocks. A Workbook, vol. 8, Schön, J.H., Ed., Kidlington: Elsevier, 2011.

Potapov, O.A., Lizun, S.A., Kondrat, V.F., et al., *Osnovy seismoelektrorazvedki* (Basics of Seismoelectric Prospecting), Moscow: Nedra, 1995.

Pride, S.R., Governing equations for the coupled electromagnetics and acoustics of porous media, *Phys. Rev.*, 1994, vol. B50, pp. 15678–15696.

Revil, A. and Jardani, A., Seismoelectric response of heavy oil reservoirs: theory and numerical modelling, *Geophys. J. Int.*, 2010, vol. 180, pp. 781–797.

Revil, A., Jardani, A., Sava, P., and Haas, A., *The Seismoelectric Method: Theory and Applications*, Chichester: Wiley, 2015.

Surkov, V.V., *Elektromagnitnye effekty pri zemletryaseniyakh i vzryvakh* (Electromagnetic Effects from Earthquakes and Explosions), Moscow: MIFI, 2000.

Svetov, B.S., *Osnovy geoelektriki* (Basics of Geoelectrics), Moscow: LKI, 2008.

Svetov, B.S., Self-consistent problems of geoelectrics, in *Electomagnetic Sounding of the Earth's Iinterior: Theory, Modeling, Practice*, 2nd ed., Spichak, V.V., Ed., Amsterdam: Elsevier, 2015, pp. 79–106.

Thompson, R.R., The seismic-electric effect, *Geophysics*, 1936, vol. 1, no. 3, pp. 48–51.

West, M., Sanchez, J.J., and McNutt, S.R., Periodically triggered seismicity at Mount Wrangell, Alaska, after the Sumatra earthquake, *Science*, 2005, vol. 308, pp. 1144–1146.

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