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Multifactor Estimation of Ecological Risks Using Numerical Simulation

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Abstract. In this paper, the problem of interaction of acoustic waves falling at a given angle on a snow layer on the ground and seismic waves arising both in this layer and in the ground is considered. A system of differential equations with boundary conditions describing the propagation of incident and reflected acoustic waves in the air refracted and reflected from the boundary of seismic waves in elastic media (snow and ground) is constructed and solved for a three-layer air-snow layer-ground model. The coefficients of reflection and refraction are calculated in the case of an acoustic wave falling onto both the ground and snow on the ground. The ratio of the energy of the refracted waves to the energy of the falling acoustic wave is obtained. It is noted that snow has a strong influence on the energy transfer into the ground, which can decrease by more than an order of magnitude. The numerical results obtained are consistent with the results of field experiments with a vibrational source performed by the Siberian Branch of the Russian Academy of Sciences.

INTRODUCTION

An important modern geoecological problem is that of predicting the impact of technogenic (quarry, polygon) and natural (earthquakes, volcanic eruptions) explosions on the environment. It is well-known that the main geoecological effects of explosions are associated with the formation of shock acoustic and seismic waves. Of greatest interest is study of seismic and acoustic effects from mass explosions, since they determine the integrity of industrial and residential objects. Earlier some authors considered the meteofactors increasing the environmental risks from explosions ([1] and [2]). At the same time, there are factors that lead to weakening of acoustic vibrations from explosions. These include the presence of a snow cover, forest massifs, and rugged terrain along the propagation path of acoustic waves.

The problem of acoustic oscillations propagation under such conditions is a multi-factor one, and its solution in full statement is rather complicated. Particular statements of the problems of acoustic oscillations propagation associated with the estimation of the influence of individual factors on the characteristics of propagation were considered earlier [3, 4, 5]. These include the characteristics of attenuation caused by the influence of snow cover on the surface propagation of acoustic oscillations [6]. The results of experiments on the interaction of acoustic oscillations with a medium represented by a "snow layer" on the Earth's surface were presented. The phenomenon of "screening" of the snow layer by the action of acoustic waves on Earth's surface was discovered experimentally.

In the present paper, an "air – poroelastic (snow) layer – elastic half-space (ground)" model is considered. The problem of interaction of acoustic waves falling at a given angle on a snow layer lying on an elastic half-space with seismic waves arising both in the snow layer and in the elastic half-space modeling the ground is studied. The

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problem of the influence of the snow cover on the amplitude of seismic waves excited in the elastic half-space is investigated. A system of differential equations with boundary conditions is constructed. It describes the propagation of incident and reflected acoustic waves in the air, and refracted and reflected seismic waves in elastic media for a three-layer "air-snow-ground" model. The amplitudes and coefficients of reflection and refraction of acoustic and seismic waves are calculated and analyzed depending on the snow layer thickness.

PROBLEM STATEMENT

We consider a three-layer model consisting of an acoustic medium (air), a poroelastic layer (snow), and an elastic half-space (ground). We assume that a harmonic acoustic wave with a given frequency falls from the air onto the poroelastic layer at angle θ ($0 \le \theta \le 90^{o}$) to the vertical. In this model the air occupies the upper half-space with sound velocity c and density ρ. The snow medium is the middle layer with given densities of the dry rock and saturating fluid, the velocities of longitudinal and transverse waves. The ground occupying the lower half-space is characterized by density and velocities of longitudinal and transverse waves (Figure 1). It is assumed for simplicity that at large distances from the source the spherical wave field is locally flat and admits twodimensional modeling.

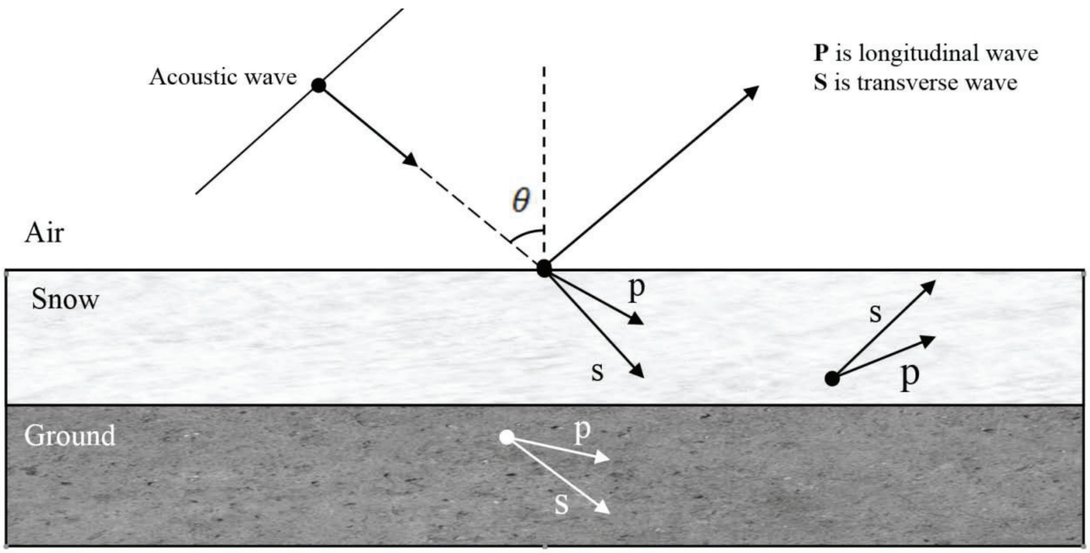


FIGURE 1. The three-layer model consisting of air, poroelastic layer (snow) and elastic half-space (ground)

The harmonic acoustic wave falling on the boundary with the poroelastic snow layer generates a reflected wave in the air, which also be harmonically dependent on time. Simultaneously refracted seismic harmonic (both longitudinal and transverse) waves are excited in the poroelastic layer. Then there emerge two waves reflected from the boundary with the elastic half-space and two refracted waves within the elastic half-space.

We consider the following wave equations for air:

$$\frac{1}{c^2}\frac{\partial^2 p}{\partial t^2} - \Delta p = 0; \quad \rho\frac{\partial \vec{u}}{\partial t} + \nabla p = 0 \,, \tag{1}$$

where p, u, and c are the pressure, the displacement vector, and the sound velocity in the air.

For the snow layer we use the Gassman model [7], which allows us to consider the complex porous structure of snow as an elastic medium. In the Gassmann model the effective elastic moduli of porous material and the velocity of longitudinal and transverse waves have the form

$$K = K_e + \frac{(1-\mathrm{K}_e/\mathrm{K}_s)^2}{n/K_f + (n-1)/\mathrm{K}_s - \mathrm{K}_e/\mathrm{K}_s^2}, \quad \mu = \mu_e, \quad \rho = \rho_s(1-\mathrm{n}) + \rho_f n \,,$$
$$V_P = \sqrt{\frac{K+4/3\mu}{\rho}}, V_S = \sqrt{\frac{\mu}{\rho}} = \sqrt{\frac{\mu_s}{\rho}}, \tag{2}$$

where $n=V_{void}/V$ is the porosity equal to the ratio of the volume of voids to the total volume; K, μ, ρ are the effective elastic moduli of the saturated solid; K_s, μ_s, ρ_s, K_f, and ρ_f are the elastic moduli of the frame and fluid, respectively; K_e, μ_e are the effective elastic moduli of the unsaturated solid frame.

For the poroelastic snow layer in the Gassman model and the elastic half-space (ground) the dynamic Lame elasticity equations with elastic characteristics for snow λ_{snow}, μ_{snow}, and ρ_{snow} obtained from (2) and for the ground with the coefficients λ_{gr}, μ_{gr}, and ρ_{gr} are solved. The equations have the following form

$$\begin{aligned}&(\lambda_{snow}+\mu_{snow})\mathrm{grad}\cdot\mathrm{div}u_{snow}+\mu\Delta u_{snow}-\rho_{snow}\cdot\frac{\partial^2 u_{snow}}{\partial t^2}=0\\&(\lambda_{gr}+\mu_{gr})\mathrm{grad}\cdot\mathrm{div}u_{gr}+\mu\Delta u_{gr}-\rho_{gr}\cdot\frac{\partial^2 u_{gr}}{\partial t^2}=0\end{aligned}. \tag{3}$$

The boundary conditions for Eqs. (1) and (3) at the "air-snow layer" boundary are the equality of the normal components of the stress tensors and the snow medium velocities and atmospheric pressure. The condition at the "snow layer-ground" boundary is the equality of the stress tensor components and the velocities of the both media at the interface. As a result, taking into account (1), (3) and the boundary conditions, we obtain a system of differential equations for the "air-snow-ground" model

$$\begin{aligned}&\frac{1}{c^2}\frac{\partial^2 p}{\partial t^2}-\Delta p=0;\quad \rho\frac{\partial\vec{u}}{\partial t}+\nabla p=0\\&(\lambda_{\text{snow}}+\mu_{\text{snow}})\mathrm{grad}\cdot\mathrm{div}u_{\text{snow}}+\mu\Delta u_{\text{snow}}-\rho_{\text{snow}}\cdot\frac{\partial^2 u_{\text{snow}}}{\partial t^2}=0\\&\sigma_{xz\text{snow}}\big|_{z=0}=0,\ \sigma_{zz\text{snow}}\big|_{z=0}=p\,\mathrm{e}^{i(\omega t-kx)},\ u_{z\text{air}}\big|_{z=0}=u_{zsnow}\big|_{z=0}\\&(\lambda_{\text{snow}}+\mu_{\text{snow}})\mathrm{grad}\cdot\mathrm{div}u_{\text{snow}}+\mu\Delta u_{\text{snow}}-\rho_{\text{snow}}\cdot\frac{\partial^2 u_{\text{snow}}}{\partial t^2}=0\\&(\lambda_{\text{gr}}+\mu_{\text{gr}})\mathrm{grad}\cdot\mathrm{div}u_{\text{gr}}+\mu_{\text{gr}}\Delta u_{\text{gr}}-\rho_{\text{gr}}\cdot\frac{\partial^2 u_{\text{gr}}}{\partial t^2}=0\\&\sigma_{xz\text{snow}}\big|_{z=h}=\sigma_{xzgr}\big|_{z=h},\ \sigma_{zzsnow}\big|_{z=h}=\sigma_{zzgr}\big|_{z=h}\\&u_{xsnow}\big|_{z=h}=u_{xgr}\big|_{z=h},\ u_{zsnow}\big|_{z=h}=u_{zgr}\big|_{z=h}\end{aligned} \tag{4}$$

where $\sigma_{xzsnow}, \sigma_{zzsnow}$, $\sigma_{xzgr}, \sigma_{zzgr}$ are the stress tensor components for the snow layer and ground; $u_{xsnow}, u_{xgr}, u_{zair}, u_{zsnow}, u_{zgr}$ are displacement components for the air, snow layer, and ground, and h is the snow thickness.

Let A_{00}=1 be the falling wave amplitude. A_{01} is the coefficient of the wave reflected from the snow; A_{10}, B_{11} are the refraction coefficients of the longitudinal and transverse waves in the snow; A_{12}, B_{13} are the reflection coefficients of the longitudinal and transverse waves in the snow; and A_{20}, B_{21} are the refraction coefficients of the longitudinal and transverse waves in the ground. It is necessary: to calculate the reflection and refraction coefficients for waves in snow and ground, to estimate the influence of snow cover on the energy of waves passing into the ground.

ALGORITHM OF FINDING REFRACTION AND REFLECTION COEFFICIENTS

The solution of Eq. (1) can be represented in the form of harmonic waves. The resulting air pressure will be written as the sum of the pressures of the falling and reflected waves:

$$P=p_0e^{i(\omega\mathrm{t}-k_x\,\mathrm{x}-k_z\,\mathrm{z})}+p_1e^{i(\omega\mathrm{t}-k_{x1}\,\mathrm{x}+k_{z1}\,\mathrm{z})},$$

where p_0, p_1 are the amplitudes of the falling and reflected waves, $\omega=2\pi f$ is the angle frequency, and $k=\omega/c$ is the wave vector directed toward the wave propagation.

In an elastic medium, the solution to the system of Eqs.(4) for velocities and stresses can be represented in the form of potentials [8, 9]:

$$\varphi=A\exp i(\omega t-kx-k_{\phi z}z),\quad \psi=B\exp i(\omega t-kx-k_{\psi z}z). \tag{5}$$

The potentials $\varphi(x,z,t)$ and $\psi(x,z,t)$ are associated with the displacement field

$$u_x=\frac{\partial\varphi}{\partial x}-\frac{\partial\psi}{\partial z},\quad u_z=\frac{\partial\varphi}{\partial z}+\frac{\partial\psi}{\partial x}. \tag{6}$$

The "air-snow" boundary conditions include the equality of the normal stress components and vertical displacement components in the two media, as well as the zero tangential stresses at the snow–air boundary

$$\begin{aligned}&\sigma_{xzsnow}\Big|_{z=0}=0,\ \sigma_{zzsnow}\Big|_{z=0}=p\,\mathrm{e}^{i(\omega t-kx)},\\&u_{zair}\Big|_{z=0}=u_{zsnow}\Big|_{z=0}.\end{aligned} \tag{7}$$

Substituting the potentials φ and ψ from (5) and (6) into the boundary conditions (7), we write the stress tensor components for snow

$$\sigma_{xz\mathrm{snow}}=\mu_{\mathrm{snow}}\left(2\frac{\partial^2\varphi_{\mathrm{snow}}}{\partial x\partial z}+\frac{\partial^2\psi_{\mathrm{snow}}}{\partial x^2}-\frac{\partial^2\psi_{\mathrm{snow}}}{\partial z^2}\right),$$

$$\sigma_{zz\mathrm{snow}}=\lambda_{\mathrm{snow}}\frac{\partial^2\varphi_{\mathrm{snow}}}{\partial x^2}+(\lambda_{\mathrm{snow}}+2\mu_{\mathrm{snow}})\frac{\partial^2\varphi_{\mathrm{snow}}}{\partial z^2}+2\mu_{\mathrm{snow}}\frac{\partial^2\psi_{\mathrm{snow}}}{\partial x\partial z}.$$

The boundary conditions at the "snow-ground" boundary have the form

$$\begin{aligned}&\sigma_{xz\mathrm{snow}}\Big|_{z=h}=\sigma_{xzgr}\Big|_{z=h},\ \sigma_{zz\mathrm{snow}}\Big|_{z=h}=\sigma_{zz\mathrm{gr}}\Big|_{z=h}\\&u_{x\mathrm{snow}}\Big|_{z=h}=u_{x\mathrm{gr}}\Big|_{z=h},\ u_{z\mathrm{snow}}\Big|_{z=h}=u_{z\mathrm{gr}}\Big|_{z=h}\end{aligned}, \tag{8}$$

where $\sigma_{xzsnow},\sigma_{zzsnow}$, $\sigma_{xzgr},\sigma_{zzgr}$ are the components of the stress tensors for snow and ground. Then we equate the displacement components for snow and ground from the boundary conditions (8)

$$\frac{\partial\varphi_{snow}}{\partial x}-\frac{\partial\psi_{snow}}{\partial z}=\frac{\partial\varphi_{\mathrm{gr}}}{\partial x}-\frac{\partial\psi_{\mathrm{gr}}}{\partial z}.$$

Equating the components of displacement z and stress tensors in (8), we obtain

$$\frac{\partial\varphi_{\mathrm{snow}}}{\partial z}+\frac{\partial\psi_{\mathrm{snow}}}{\partial x}=\frac{\partial\varphi_{\mathrm{gr}}}{\partial z}+\frac{\partial\psi_{\mathrm{gr}}}{\partial x},$$

$$\sigma_{xzsnow}=\sigma_{xzgr}. \tag{9}$$

Substituting the potentials φ and ψ from (5) and (6) into the boundary conditions (8), we can write the stress tensor components for snow and ground (9)

$$\mu_{\mathrm{snow}}\left(2\frac{\partial^2\varphi_{\mathrm{snow}}}{\partial x\partial z}+\frac{\partial^2\psi_{\mathrm{snow}}}{\partial x^2}-\frac{\partial^2\psi_{\mathrm{snow}}}{\partial z^2}\right)=\mu_{\mathrm{gr}}\left(2\frac{\partial^2\varphi_{\mathrm{gr}}}{\partial x\partial z}+\frac{\partial^2\psi_{\mathrm{gr}}}{\partial x^2}-\frac{\partial^2\psi_{\mathrm{gr}}}{\partial z^2}\right). \tag{10}$$

Similarly, we equate the normal stress components in (8)

$$\sigma_{zzsnow}=\sigma_{zzgr}.$$

$$\lambda_{\mathrm{snow}}\frac{\partial^2\varphi_{\mathrm{snow}}}{\partial \mathrm{x}^2}+(\lambda_{\mathrm{snow}}+2\mu_{\mathrm{snow}})\frac{\partial^2\varphi_{\mathrm{snow}}}{\partial \mathrm{z}^2}+2\mu_{\mathrm{snow}}\frac{\partial^2\psi_{\mathrm{snow}}}{\partial \mathrm{x}\partial \mathrm{z}}=\lambda_{\mathrm{gr}}\frac{\partial^2\varphi_{\mathrm{gr}}}{\partial \mathrm{x}^2}+(\lambda_{\mathrm{gr}}+2\mu_{\mathrm{gr}})\frac{\partial^2\varphi_{\mathrm{gr}}}{\partial \mathrm{z}^2}+2\mu_{\mathrm{gr}}\frac{\partial^2\psi_{\mathrm{gr}}}{\partial \mathrm{x}\partial \mathrm{z}}. \tag{11}$$

As a result of all transformations into (10) and (11), we obtain seven expressions for the seven unknown coefficients of reflection and refraction. Combining all seven expressions, we obtain a system of linear algebraic equations (SLAE) of the form $Fx=C$, where x is the column vector of the solution to the SLAE $x=(A_{01},A_{02},A_{10},A_{11},A_{12},A_{20},A_{21})^T$ to be found, F is a 7×7 matrix consisting of values for the unknown reflection and refraction coefficients, and C is the column vector in the right-hand side

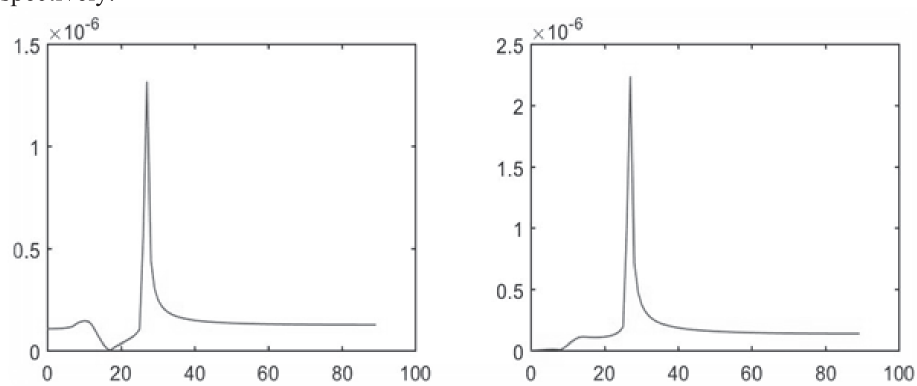
$$C=(A_{00}\cos\theta/\rho c,0,A_{00},0,0,0,0)^T. \tag{12}$$

$$F=\begin{bmatrix} -\dfrac{\cos\theta}{\rho c} & -\mathrm{i}\,\mathrm{k}_{10z} & -\mathrm{i}\,\mathrm{k}_{x} & 0 & 0 & 0 & 0 \\ 0 & f_{22} & f_{23} & 0 & 0 & 0 & 0 \\ -1 & f_{32} & 2\mu_{snow}k_x k_{11z} & 0 & 0 & 0 & 0 \\ 0 & -k_x e^{-ik_{10z}h} & k_{11z}e^{-ik_{11z}h} & -k_x e^{ik_{12z}h} & -k_{13z}e^{-ik_{13z}h} & k_x e^{-ik_{20z}h} & -k_{21z}e^{-ik_{21z}h} \\ 0 & -k_{10z}e^{-ik_{10z}h} & -k_x e^{-ik_{11z}h} & k_{12z}e^{ik_{12z}h} & -k_x e^{ik_{13z}h} & k_{20z}e^{-ik_{20z}h} & k_x e^{-ik_{21z}h} \\ 0 & f_{62} & f_{63} & f_{64} & f_{65} & f_{66} & f_{67} \\ 0 & f_{72} & f_{73} & f_{74} & f_{75} & f_{76} & f_{77} \end{bmatrix}, \qquad (13)$$

where $f_{23}=\mu_{snow}(\mathrm{k}_x^2-\mathrm{k}_{11z}^2)$ $f_{22}=2\mu_{snow}\,\mathrm{k}_x\,k_{10z}$ $f_{32}=(\lambda_{snow}\,\mathrm{k}_x^2+(\lambda_{snow}+2\mu_{snow})k_{10z}^2)$, $f_{62}=2\mu_{snow}k_x k_{10z}e^{-ik_{10z}h}$, $f_{63}=\mu_{snow}(\mathrm{k}_x^2-\mathrm{k}_{11z}^2)e^{-ik_{11z}h}$, $f_{64}=-2\mu_{snow}k_x k_{12z}e^{ik_{12z}h}$, $f_{65}=\mu_{snow}(\mathrm{k}_x^2-\mathrm{k}_{13z}^2)e^{ik_{13z}h}$, $f_{66}=-2\mu_{gr}k_x k_{20z}e^{-ik_{20z}h}$, $f_{67}=\mu_{gr}(\mathrm{k}_{21z}^2-\mathrm{k}_x^2)e^{-ik_{21z}h}$, $\mathrm{f}_{72}=(\lambda_{snow}\,\mathrm{k}_x^2+(\lambda_{snow}+2\mu_{snow})k_{10z}^2)e^{-ik_{10z}h}$, $f_{73}=2\mu_{snow}k_x k_{11z}e^{-ik_{11z}h}$, $\mathrm{f}_{74}=(\lambda_{snow}\,\mathrm{k}_x^2+(\lambda_{snow}+2\mu_{snow})k_{12z}^2)e^{ik_{12z}h}$, $f_{75}=-2\mu_{snow}k_x k_{13z}e^{ik_{13z}h}$, $f_{76}=-(\lambda_{gr}\,\mathrm{k}_x^2+(\lambda_{gr}+2\mu_{gr})k_{20z}^2)e^{-ik_{20z}h}$, $f_{77}=-2\mu_{gr}k_x k_{21z}e^{-ik_{21z}h}$.

RESULTS OF THE NUMERICAL SIMULATION

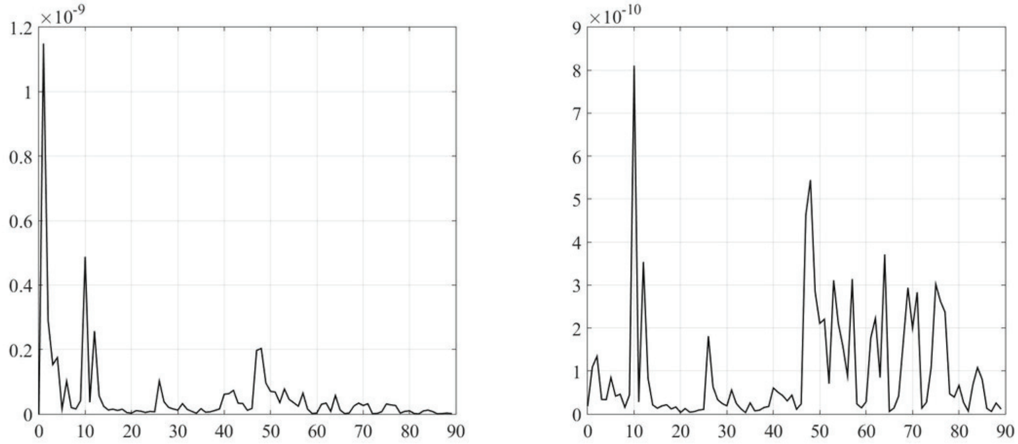
In the numerical simulation, a harmonic wave with the constant frequency f = 15Hz is considered as an acoustic wave falling at an angle to the snow layer. The air parameters are density ρ = 1.32kg/m^3 and sound velocity c = 328m/s at a temperature of −5°C. The wave vector of the falling acoustic wave is $k=\omega/c$. In the Gassman model for snow, ice is considered as the skeleton material, and air is taken as the fluid filling the pores. At −5°C the elastic parameters and the ice density have the following values: K_s=8·10^6 Pa, μ_s=3·10^6 Pa, and ρ_s =918kg/m^3. For the fluid (air), the compression modulus K_f=1.4·10^5 Pa and the density ρ_f=1.32 kg/m^3. As porosity and snow density parameters, the following tabular values for the snow cover are taken: the density ρ=3200 kg/m^3 and the porosity n=63%. With these values, the compression modulus K and the velocity of longitudinal and transverse waves in the snow is calculated from the relation (3). The longitudinal and transverse waves in the ground are V_p = 2500m/s and V_s = 1800m/s, respectively.



a) b)

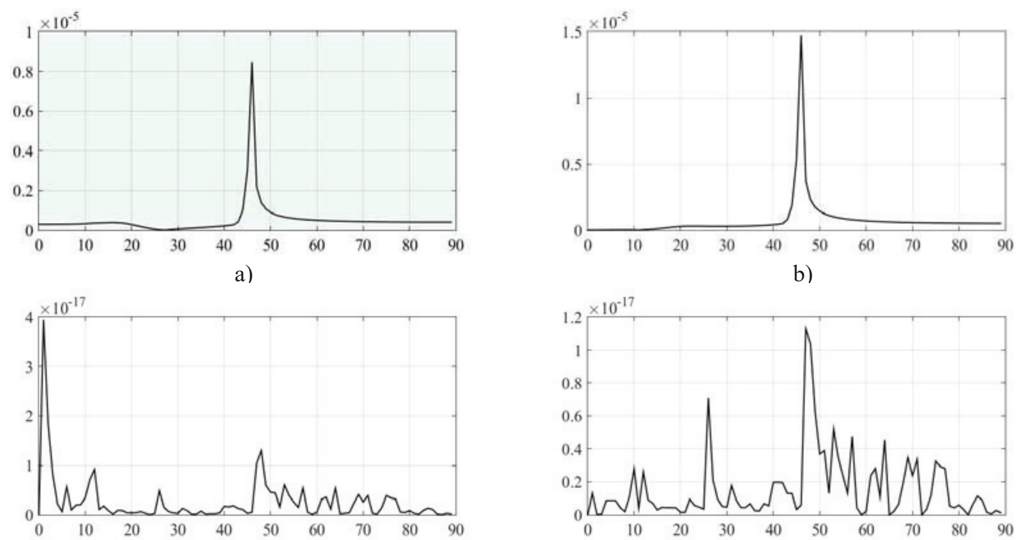
FIGURE 2. Graphs of refraction coefficients (a) longitudinal and (b) transverse waves for ground without the snow layer. Along the horizontal axis the angle of the falling acoustic wave

The numerical simulation was carried out in the MATLAB with the media parameters specified above. The SLAE was constructed with the right-hand side of (12) and the matrix of the form (13). The reflection and refraction coefficients were obtained in the form of the SLAE solution vector [9]. For the case of an acoustic wave falling onto the ground without a snow layer, the curves of the refracted and reflected wave coefficients are shown in Figure 2. The wave energy was estimated from the formula $E_P/E=\rho_p/\rho\ |k_p/k|^2A^2$, where E_P is the refracted wave energy, E is the initial wave energy, ρ_p/ρ is the ratio of the media densities, and k_p/k is the ratio of the wave vectors of the initial and refracted waves. Figures 3 and 4 show the curves of the refraction and reflection coefficients, respectively, in the case of acoustic wave propagation through snow. One can see from the numerical results and curves that the snow layer greatly absorbs the incoming acoustic wave energy from the air.



a) b)

FIGURE 3. Graphs of refraction coefficients a) for longitudinal wave in the snow; b) for transverse wave in the snow. Along the horizontal axis the angle of the falling acoustic wave



a) b) c) d)

FIGURE 4. Graphs of the refraction coefficients:a) for longitudinal wave in the snow; b) for transverse wave in the snow; c) for longitudinal wave in the ground; d) for transverse wave in the ground. Along the horizontal axis the angle of the falling acoustic wave

In this case, high values of the refraction coefficients of acoustic waves in the snow are determining factors (Figure 4a and 4b) caused by dominant levels of refracted longitudinal and transverse waves in the snow layer. The levels of refraction waves of this type are several orders of magnitude lower (Figure 4c and 4d).

RESULTS OF FIELD EXPERIMENTS

The results of the numerical simulation were compared with the experimental data obtained for 2013-2014. Sessions of vibrational sounding of the two-layer “atmosphere-ground” medium using seismoacoustic oscillations from a CV-40 vibrator were performed. The frequency range of the source is from 6 to 10Hz and the perturbing force amplitude is 40tf. This source simultaneously excites seismic oscillations in the Earth and acoustic oscillations in the atmosphere. In the experiments the both types of oscillations were recorded at a distance of 50 km from the source by a 3-component SK1-P sensor and an acoustic PDS-7 sensor.

As a method of accumulation of weak vibrational oscillations on the background of external noise we used cross-correlation convolution of the recorded low-amplitude oscillations with the reference signal. The signal was synthesized at the recording point and repeated the shape of the radiated sounding oscillation. As a result of the cross-correlation convolution of acoustic and seismic oscillations, we obtained, respectively, acoustograms and seismograms (Figure 5). The acoustic wave comes at 142 sec to the seismic sensor SK1-P (Figure 5a). The presence of acoustic waves can be explained by the effect of acoustoseismic induction. The acoustic wave propagates in the low atmosphere and induces a surface wave in the ground. The induced wave propagates in the ground at the speed of infrasound.

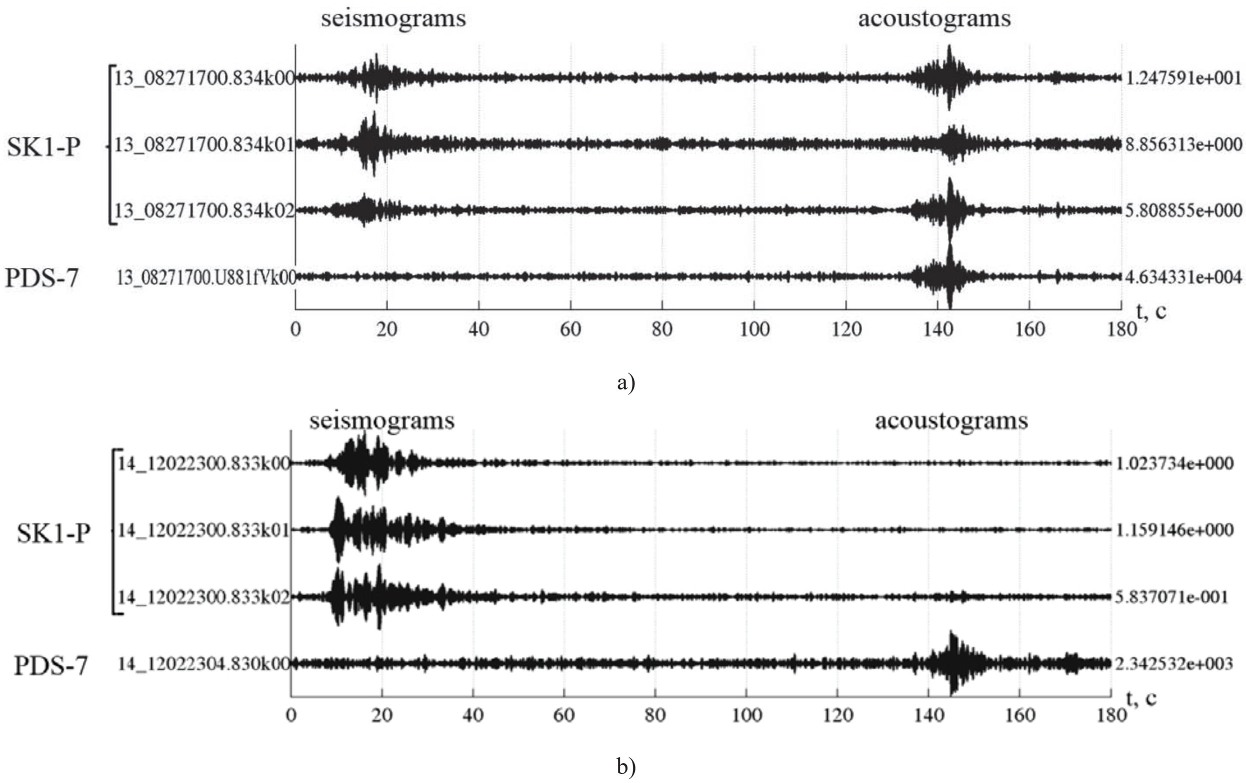


FIGURE 5. Example of the acoustograms and seismograms. Distance from source of 50 km

If snow cover is present, we have the effect of screening of acoustic waves from penetration into the surface ground layer. This greatly decreases the acoustic wave levels on the seismic sensor SK1-P (Figure 5b). At the same time, the acoustic wave levels on the acoustic sensor PDS-7 located in the air remain invariably high (bottom part of Figure 5b).

Figure 6 shows the ratio of the acoustic wave levels recorded by the SK1-P and PDS-7 at different times of the year and, correspondingly, the snow cover thickness from 0 to 67 centimetres. A comparative analysis has shown that if snow is present, the acoustic wave levels recorded by the ground-based seismic sensors can decrease depending on the snow cover thickness by more than an order of magnitude. Thus, Figure 5 and 6 confirm the influence of the factors of reflection and absorption of acoustic waves identified using theoretical analysis.

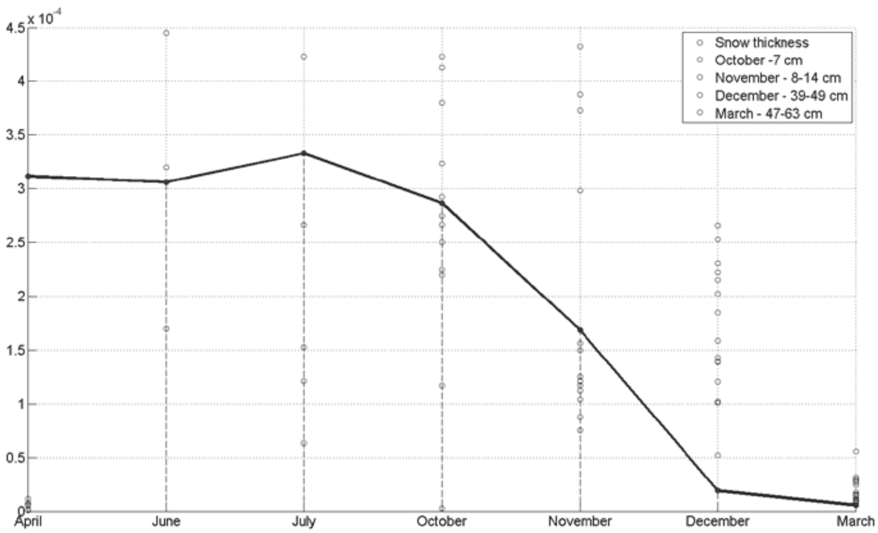


FIGURE 6. The ratio of the acoustic wave levels recorded by the SK1-P seismic sensor and the acoustic PDS-7 at different months of the year.

The results of experimental studies (Figures 5 and 6) show an important physical phenomenon of screening of acoustic waves, leading to strong weakening of the acoustoseismic induction effect. This effect is associated with the formation of a surface seismic wave when the acoustic wave propagation in the lower atmosphere. We experimentally proved that the presence of a snow layer substantially weakens such effect. Thereby the results of numerical simulation explain such attenuation. In the snow layer, the incident acoustic wave from the air is transformed into refracted longitudinal and transverse waves (Figure 4a and 4b). Simultaneously these waves in the underlying ground have levels lower by several orders of magnitude (Figure 4c and 4d). This is the relation between Figure 5 and 6 on the one hand, and Figure 4 on the other.

CONCLUSION

The problem of interaction of acoustic waves falling at a given angle on a snow layer on the ground and seismic waves arising both in the snow layer and in the ground is considered. A system of differential equations with boundary conditions describing the propagation of falling and reflected acoustic waves in the air refracted and reflected from the boundary of seismic waves in elastic media (snow and ground) for a three-layer “air-snow-ground” model has been constructed and solved. The coefficients of reflection and refraction have been calculated for the case of an acoustic wave falling onto the ground and snow on the ground. The ratio of the energy of the refracted waves to the energy of the incident acoustic wave has been obtained.

It has been shown that the snow cover thickness has a strong influence on the transfer of acoustic wave energy into the ground, which can decrease by more than an order of magnitude. This is a manifestation of the effect of screening of acoustic waves. The numerical results obtained are in agreement with the results of field experiments at a distance of 50km and demonstrate the screening effect based on comparison of the levels of acoustic and surface seismic waves.

The results of the theoretical and experimental investigations are of practical importance in the problem of detection of acoustic waves by seismic methods.

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REFERENCES

1. M.S. Khairetdinov, G.M. Voskoboynikova, V.V. Kovalevsky, and G.F. Sedukhina, “Multifactorial rediction of geoecological risks from powerful explosions with application the vibroseismic method,” in *Proceedings of 12th International Forum on Strategic Technology (IFOST-2017)*, (University of Ulsan, Korea, 2017), pp.350‒355.
2. M.S. Khairetdinov, V.V. Kovalevskiy, G.M. Voskoboynikova *et al* (2016) Estimation of meteo dependent geoecological risks from explosions using seismic vibrators, *Seismic Exploration Technology* **3**, 132–138. [in Russian]
3. A.V. Razin, and A.L. Sobisevich, *Geoacoustics of Layered Media* (Institute of the Earth’s Physics RAS, Moscow, 2012), 210p. [in Russian]
4. Yu.V. Petukhov, A.V. Razin, A.L. Sobishevich, and V.I Kulikov, *Seismoacoustic and Acoustic-Gravitational Waves in Layered Media* (IPE RAS, Moscow, 2013), 280p. [in Russian]
5. V.V. Sitnik (2009) Vegetation array influence on acoustic waves propagation, *Mathematical Modeling* **19**(8), 90‒96. [in Russian]
6. G. Voskoboynikova, Kh. Imomnazarov, A. Mikhailov and Jian-Gang Tang, “Influence of snow cover on the seismic waves propagation,” in *Proceedings of Sixth Conference on Numerical Analysis and Applications (NAA’16)*, (University of Rousse, Bulgaria, 2016), pp. 697‒703.
7. E.A. Marfin and M.N. Ovchinnikov, “Elastic Waves in Porous Saturated Solid”, Textbook, Kazan State University, 2012, 28p. [in Russian]
8. V.V. Kovalevskiy (2005) Investigation of the acousto seismic wave fields generated by surface seismic vibrators, *Acoustic Journal* **51**, 104‒-114. [in Russian]
9. A.Yu. Rojko (2003) Interaction of acoustic and seismic waves (Reflection-refraction waves from the “Earth-air” boundary), *Physical Meso Mechanics* **6**(1), 23‒31. [in Russian]