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SEISMIC EFFICIENCY OF A CONTACT EXPLOSION AND A HIGH-VELOCITY IMPACT

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The seismic energy transferred to an elastic half-space as a result of a contact explosion and a meteorite impact on a planet's surface is estimated. The seismic efficiency of the explosion and impact are evaluated as the ratio of the energy of the generated seismic waves to the energy of explosion or the kinetic energy of the meteorite. In the case of contact explosions, this ratio is in the range of 10^{-4}*–*10^{-3}*. In the case of wide-scale impact effects, where the crater in the planet's crust is produced in the gravitational regime, a formula is derived that relates the seismic efficiency of an impact to its determining parameters.*

Key words: *contact explosion, impact, seismic efficiency.*

Introduction. Estimating the seismic energy transferred to the medium as a result of underground explosions and impacts of space bodies on the Earth is important for predictions of the seismic effect on engineering facilities, biota, the Earth's crust, and the planet as a whole.

The energy of seismic motion for underground atomic explosions is determined in [1], where it is shown that the seismic efficiency (SE) $k_s \equiv E_s/E_0$ (E_s is the energy of seismic waves and E_0 is the energy of explosion) has the following values: 0.1% in alluvium, 1.2% in tuff, 4.9% in rock salt, and 3.7% in granite. These data were obtained for fairly great charge depths. As the charge depth decreases, the value k_s increases. As shown in [2], a decrease in the charge depth results in an increase in the SE to a value close to 10%.

The seismic efficiency of a high-velocity impact was evaluated in [3–8]. From the papers cited, it follows that the value of k_s was estimated with a large error ($k_s = E_s/E_0 = 10^{-6}$–10^{-2}, where E_0 is the kinetic energy). Its dependence on the parameters determining the seismic effect of impacts is also unclear. The value k_s for contact explosions is not known.

The object of the present study is to obtain the functional dependence of the seismic efficiency on the determining parameters in the cases of contact explosions and high-velocity impacts.

1. Confined Explosion. The seismic effect of a confined underground explosion in rock is described using the Haskell model [1]. The longitudinal P-wave generated by an explosion is characterized by the potential $\varphi(t,r)$ of the displacement field $u(t,r)$ of the form

$$u(t,r) = \frac{\partial\varphi(t,r)}{\partial r}, \qquad \varphi(t,r) = -\frac{\Phi(\infty)}{r}\, f(\tau), \qquad \tau = \frac{1}{t_0}\Big(t - \frac{r}{c_P}\Big),$$
$$f(\tau) = 1 - \mathrm{e}^{-\tau}(1 + \tau + \tau^2/2 + \tau^3/6 - B\tau^4). \tag{1.1}$$

Here t is the time reckoned from the time of explosion, r is the distance from the point of explosion, c_P is the propagation velocity of the longitudinal waves, and $f(\tau)$ is a function of the source equivalent in the generated P-wave to the explosion. Relation (1.1) contains three free parameters: t_0, $\Phi(\infty)$, and B, which are chosen from experiments. The physical meaning of these parameters is as follows. The parameter t_0 determines the time scale of

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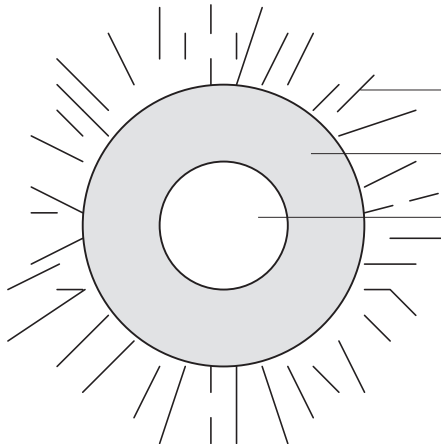

Fig. 1. Diagram of rock fracture in a confined explosion (according to Rodionov [9]): 1) camouflet cavity; 2) fracture region; 3) region of radial cracks.

seismic motion. In this case, the characteristic length defining the dimensions of the seismic source (the explosion source) $c_P t_0$ is approximately equal to the radius of the region of rock fracture surrounding the central region of the explosion (Fig. 1). In the case of great explosion sources $c_P t_0 \approx r_e$ (r_e is the elastic radius of the explosion source). In the case of shallow explosion source depths, the elastic radius is close to the radius of the region of radial cracks [9].

The parameter $\Phi(\infty)$ is equal to within 4π to the volume displaced into the elastic-strain region:

$$V_\infty = 4\pi\Phi(\infty) \tag{1.2}$$

(V_∞ is the displaced volume). If a region of radial cracks (great explosion source depth) is absent and if rock compaction and loosening at the explosion source can be ignored, the volume V_∞ is equal to the volume of the camouflet cavity:

$$V_\infty \approx (4/3)\pi r_{\rm cav}^3 \tag{1.3}$$

($r_{\rm cav}$ is the radius of the camouflet cavity). Relations (1.2) and (1.3) imply the approximated ratio $\Phi(\infty) \approx r_{\rm cav}^3/3$. The radius of the camouflet cavity can be found from the well-known empirical formulas given in [10, 11].

The parameter B ($0 \leqslant B < 0.5$) depends on the properties of the medium in which the explosion occurs (density, porosity, water saturation, lithostatic pressure, etc.). In the elastic model, this parameter is a function of only Poisson's coefficient ν. There is a weak correlation between B and ν. As a rough approximation, we can set $B \approx \nu$.

The source (1.1) produces the displacement and stress fields described by the formulas

$$\frac{u}{c_P t_0} = \varkappa\Big(\frac{f(\tau)}{R^2} + \frac{f'(\tau)}{R}\Big), \qquad \frac{\sigma_{rr}}{\rho c_P^2} = -\varkappa\Big(4\gamma^2\frac{f(\tau)}{R^3} + 4\gamma^2\frac{f'(\tau)}{R^2} + \frac{f''(\tau)}{R}\Big),$$

$$\frac{\sigma_{\theta\theta}}{\rho c_P^2} = \frac{\sigma_{\varphi\varphi}}{\rho c_P^2} = \varkappa\Big(2\gamma^2\frac{f(\tau)}{R^3} + 2\gamma^2\frac{f'(\tau)}{R^2} - (1-2\gamma^2)\,\frac{f''(\tau)}{R}\Big), \tag{1.4}$$

$$\frac{\sigma_{rr} - \sigma_{\theta\theta}}{2\rho c_P^2} = -\varkappa\Big(3\gamma^2\frac{f(\tau)}{R^3} + 3\gamma^2\frac{f'(\tau)}{R^2} + \gamma^2\frac{f''(\tau)}{R}\Big),$$

where σ_{ik} are the stress-tensor components, $R \equiv r/(c_P t_0)$, $\gamma = c_S/c_P$, and c_S is the shear-wave velocity,

$$\varkappa \equiv \Phi(\infty)/(c_P t_0)^3. \tag{1.5}$$

Below, we shall need formulas that describe the residual displacements and stresses occurring in the neighborhood of explosion source after the P-wave generation. These formulas follow from relation (1.4) as $t \to \infty$:

$$\frac{u}{c_P t_0} = \frac{\varkappa}{R^2}, \qquad \frac{\sigma_{rr}}{\rho c_P^2} = -\frac{4\gamma^2\varkappa}{R^3}, \qquad \frac{\sigma_{\theta\theta}}{\rho c_P^2} = \frac{2\gamma^2\varkappa}{R^3}, \qquad \frac{\sigma_{rr} - \sigma_{\theta\theta}}{2\rho c_P^2} = -\frac{3\gamma^2\varkappa}{R^3}. \tag{1.6}$$

The energy of the generated P-wave is defined by the formula obtained in [1]:

$$E_s = \pi\alpha(B)\varkappa\rho c_P^2\Phi(\infty), \qquad \alpha(B) = (5 + 3(1 + 24B)^2)/64. \tag{1.7}$$

Introducing the seismic moment of explosion $M_0 \equiv 4\pi\rho c_P^2\Phi(\infty)$, we write relation (1.7) as

$$E_s/M_0 = (1/4)\alpha(B)\varkappa. \tag{1.8}$$

The value of the parameter B is determined in [1] for explosions in four rocks: $B = 0.49$ in alluvium, $B = 0.05$ in tuff, $B = 0.17$ in rock salt, and $B = 0.24$ in granite. The parameter B depends not only on the properties of the rock but also on the explosion source depth. As the explosion source depth decreases, the parameter B increases. The estimate of B obtained in [2] for small camouflet depths shows that for strong rock, $B \approx 0.3$. Confining ourselves to strong effects of explosions and impact in the Earth's crust or in the crust of a different planet, we assume that the planet's crust is rock close in properties to granite. In this case, $\alpha(B)/4 \approx 0.75$ and formula (1.8) becomes

$$E_s/M_0 = 0.75\varkappa. \tag{1.9}$$

The parameter $\varkappa$ is related [through $\Phi(\infty)$] to the displaced volume V_∞, which is defined as the product of the area S_1 of the surface of the fracture region S and the residual displacement u_∞ of the points of this surface:

$$V_\infty = S_1 u_\infty = 4\pi r_e^2 u_\infty.$$

Here r_e is the radius of the surface S (the "elastic radius"). According to (1.5) and (1.6), the residual displacement u_∞ is defined by the formula

$$u_\infty = \Phi(\infty)/r_e^2. \tag{1.10}$$

If fracture results from shear deformations, on the boundary $r = r_e$, the following condition should be satisfied:

$$\sigma_s = |(\sigma_{rr} - \sigma_{\theta\theta})/2|_{r=r_e} = 3\gamma^2\varkappa\rho c_P^2(c_P t_0/r_e)^3. \tag{1.11}$$

Here σ_s is the shear strength of rock. Eliminating $\varkappa$ from (1.5), (1.10), and (1.11), we obtain

$$u_\infty = \sigma_s r_e/(3\gamma^2\rho c_P^2). \tag{1.12}$$

The definition of the parameter $\varkappa$ and formula (1.11) imply

$$\varkappa = \frac{\sigma_s}{3\mu}\Big(\frac{r_e}{c_P t_0}\Big)^3.$$

Because the quantities r_e and $c_P t_0$ are close, setting their ratio equal unit, we obtain

$$\varkappa = \frac{\sigma_s}{3\mu} = \frac{\sigma_s}{3\gamma^2\rho c_P^2} \approx \frac{\sigma_s}{\rho c_P^2}, \tag{1.13}$$

since for strong rock, $3\gamma^2 \approx 1$. Thus, the parameter $\varkappa$ is approximately equal to the ratio of the shear strength of rock to its adiabatic rigidity.

Using formulas (1.2), (1.3), and (1.5), one can show that the radii of the camouflet cavity and the rock-fracture region are related by the formula

$$r_{\text{cav}} = \Big(\frac{3\sigma_s}{\rho c_P^2}\Big)^{1/3} r_e,$$

which is close to the similar relation obtained in [9] by a somewhat different method.

In view of (1.13) formula (1.8) becomes

$$E_s/M_0 = 0.54\sigma_s/(2\mu). \tag{1.14}$$

Relation (1.14) coincides with the similar relation between seismic energy and seismic moment obtained in the theory of the earthquake source [12]:

$$E_s/M_0 = \sigma_s/(2\mu).$$

Although the conditions in an earthquake source and an explosion source differ significantly, the functional relationship between the seismic energy and seismic moment is identical in both cases:

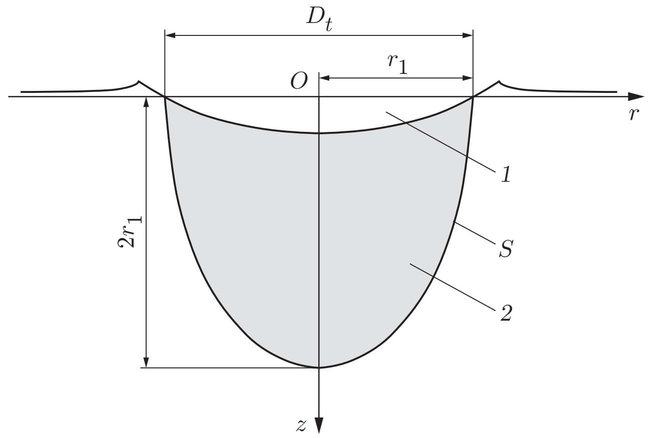

Fig. 2. Configuration of the fracture region in a contact explosion: 1) crater; 2) fracture region.

$$E_s/M_0 = c\sigma_s/\mu$$

($c = 0.5$ for earthquakes and $c = 0.27$ for explosions). This ratio depends only on the relative shear strength of the rock, which indicates similarity between the mechanisms of seismic-wave generation in explosions and earthquakes: elastic-stress relaxation by shear fracture at the source.

The seismic energy of an explosion can be written as

$$E_s = 0.75\sigma_s u_\infty S_1. \tag{1.15}$$

The product $\sigma_s u_\infty S_1 = \sigma_s V_\infty$ is the work done by strength forces to form the volume being displaced. Part of this work is converted to the energy of seismic waves. The remaining part is converted to the potential energy of elastically deformed rock in the neighborhood of the fracture region.

From relation (1.15) it follows that the energy of seismic waves can be calculated given the rock strength and the area and residual displacement of the elastoplastic boundary.

Relations (1.12) and (1.15) imply that the SE of a confined explosion can be written as

$$k_s = 0.75\rho c_P^2(\sigma_s/\mu)^2\alpha_e^3, \tag{1.16}$$

where $\alpha_e = r_e E_0^{-1/3}$ is the specific radius of the explosion source.

As an example, we estimate the SE of a confined explosion in granite. The parameters of granite are taken from [1]: $\rho = 2670$ kg/m^3, $c_P = 4.8 \cdot 10^3$ m/sec, $c_S = 0.6c_P$, and $\mu = \rho c_S^2 = 2.2 \cdot 10^{10}$ Pa. The shear strength of granite Is evaluated as $\sigma_s = (0.5–1.0) \cdot 10^8$ Pa. The values of the elastic specific radius of the explosion source and the specific reduced potential are taken to be the same as in [13]: $\alpha_e = 68$ m/kt$^{1/3} = 4.2 \cdot 10^{-3}$ m/J$^{1/3}$, and $\Phi(\infty) = 440$ m$^3/kt = 1.1 \cdot 10^{-10}$ m^3/J. As a result, we obtain $k_s \approx (2–10) \cdot 10^{-2}$, which is consistent with the estimate of [1].

2. Seismic Efficiency of a Contact Explosion. From the aforesaid it follows that the SE of an explosion is determined by parameters with the dimension of volume: the reduced potential $\Phi(\infty)$, the displaced volume $V_\infty = 4\pi\Phi(\infty)$, and the volume of the fractured medium $V_* = (4/3)\pi r_e^3 \approx (4/3)\pi(c_P t_0)^3$.

The seismic efficiency of an earthquake is determined by the displaced volume $V_1 = uS_1$ (u is the average displacement along the fault surface S). The value of each of the indicated volumes is proportional to the seismic energy transferred from the source to the ambient elastic medium.

The seismic efficiency of a contact explosion can also be estimated from the values of the above-mentioned volumes by comparing them with the corresponding volumes of the confined explosion.

Let us introduce a circular cylindrical coordinate system $Orz\theta$ with the r axis directed along the free surface and the z axis directed downward. We place the origin at the explosion center. By virtue of the presumed rotational symmetry, the motion does not depend on the angular coordinate θ. The explosion produces an ejection crater and an adjacent region of fractured rock (Fig. 2).

As shown in [14], the fracture at the site of explosion propagates to a depth $z = 2r_1$ (r_1 is the radius of fracture along the free surface). From [15] it follows that the boundary of the fracture region S has an oval shape close to the shape of the surface of half of an ellipsoid of revolution elongated in the z direction. We approximate the surface S by the surface of an ellipsoid of revolution with semiaxes $a = 2r_1$ and $b = r_1$. The distance $r = r_1$ from the center of the explosion to the boundary of fracture along the free surface is assumed to be equal to the radius of the ejection crater. From experiments [9] it follows that $r_1 \approx (20\text{–}22)$ m/kt$^{1/3} \approx 1.3 \cdot 10^{-3}$ m/J$^{1/3}$. The area of the surface S is equal to

$$S_1 = \pi ab\Big(\sqrt{1-\varepsilon^2} + \frac{\arcsin\varepsilon}{\varepsilon}\Big) = 2\pi r_1^2\Big(\frac{1}{2} + \frac{2\pi}{3\sqrt{3}}\Big) = 10.7r_1^2, \qquad (2.1)$$

where $\varepsilon = \sqrt{(a^2 - b^2)/a^2} = \sqrt{3}/2$ is the eccentricity of the ellipse; $\arcsin\varepsilon = \pi/3$. The volume of the fracture region is equal to

$$V_1 = \frac{1}{2}\Big(\frac{4}{3}\,\pi ab^2\Big) \approx 4r_1^3.$$

For $r_1 = 21$ m/kt$^{1/3}$, we obtain $S_1 = 4.7 \cdot 10^3$ m^2/kt$^{2/3}$ = 4 m^2/J$^{2/3}$, and $V_1 = 3.7 \cdot 10^4$ m^3/kt $\approx 10^{-8}$ m^3/J. In calculating the displaced volume $V_\infty = uS_1$, as the average displacement, we use the quantity

$$u = \sigma_s r_1/(3\mu). \qquad (2.2)$$

Here r_1 is the average radius of the surface S (a quantity close to the average radius of the volume V_1). As a result, we obtain $V_\infty = 3.6(\sigma_s/\mu)r_1^3E_0$, $E_s = \rho c_P^2(\sigma_s/\mu)^2r_1^3E_0$ and

$$k_s = \rho c_P^2(\sigma_s/\mu)^2r_1^3. \qquad (2.3)$$

Let us compare the SE of a contact explosion (2.3) and a confined explosion (1.16) for $r_1 = 21$ m/kt$^{1/3}$ and $\alpha_e = 68$ m/kt$^{1/3}$. Their ratio is approximately equal to $3 \cdot 10^{-2}$. The SE of a confined explosion in granite is $k_s \approx (2\text{–}10) \cdot 10^{-2}$, whereas the same value for a contact explosion is $k_s \approx (0.7\text{–}3.0) \cdot 10^{-3}$.

3. Seismic Efficiency of a High-Velocity Impact. The SE of a high-velocity meteorite impact on a planet can be estimated in the same way is in the case of a contact explosion. In the case of an impact, as in the case of an explosion, an ejection crater is formed and the crust under the crater is fractured. The diameter of the fracture region along the free surface is approximately equal to the diameter of the crater but fracture propagates to a larger depth than in explosions. During an explosion, fracture reaches a depth equal to the crater diameter, and during an impact, it reaches a depth larger than the penetration of the impactor $\Delta l \approx L\sqrt{\rho_p/\rho_t}$ (L is the impactor diameter, ρ_p is its density, and ρ_t is the density of the crust) [8]. The crater diameter is approximately five times the impactor diameter; therefore, $L \approx 0.2D_t$, and the distance to the lower boundary of the fracture region (the Fig. 3) is equal to

$$r_2 = D_t(1 + 0.2\sqrt{\rho_p/\rho_t}\,).$$

Here D_t is the diameter of the transient crater, i.e., the crater diameter at the end of excavation (ejection) of the target rock (the apparent diameter measured at the level of the initial target surface).

The configuration of the fracture region, as in the case of a contact explosion, is approximated by a semiellipsoid of revolution with semiaxes $a = D_t(1 + 0.2\sqrt{\rho_p/\rho_t}\,)$ and $b = 0.5D_t$.

As is known, the formation of an impact crater of fairly large dimensions occurs in the so-called gravitational regime, in which the crater dimensions are determined primarily by the gravity on the planet's surface (the gravitational regime of the formation of an impact crater on the Earth occurs at $D_t \geqslant 3$ km, and on the Moon, it occurs at $D_t \geqslant 20$ km) [8]. In this case, for a constant value of the ratio ρ_p/ρ_t, the quantity D_t is determined only by the dimensionless parameter $1.61gL/v_i^2$:

$$D_t = C(m/\rho_t)^{1/3}(1.61gL/v_i^2)^{-\beta}. \qquad (3.1)$$

Here m and v_t are the mass and velocity of the impactor, g is the acceleration of gravity on the planet's surface, and C and β are constants determined from experiments. If the target material is strong rock, $C = 1.6$ and $\beta = 0.22$ [8].

Substitution of (3.1) into (2.1) yields the surface area of the fracture boundary

$$S_1 = \frac{\pi}{2}\Big(1 + 0.2\sqrt{\frac{\rho_p}{\rho_t}}\Big)D_t^2\Big(\sqrt{1-\varepsilon^2} + \frac{\arcsin\varepsilon}{\varepsilon}\Big).$$

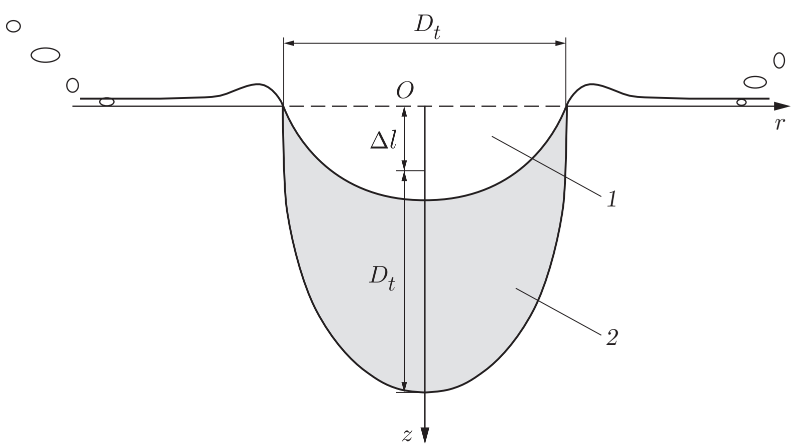

Fig. 3. Configuration of the fracture region in an impact: 1) transient crater; 2) fracture region.

TABLE 1

Values of the Parameter $\alpha_t = gL_t/c_P^2$ for Terrestrial Planets

Planet	L_t, km	g, m/sec^2	c_P, km/sec	α_t
Mercury	4880	3.70	7.35	0.33
Venus	12,100	8.57	6.00	3.00
Earth	12,760	9.81	6.30	3.20
Mars	6800	3.78	6.00	0.71
Moon	3475	1.62	5.00	0.31

The displacement of the points of the boundary is estimated, as in an explosion, by formula (2.2):

$$u = \sigma_s r_1/(3\mu), \qquad r_1 = (S_1/\pi)^{1/2}.$$

Next, we obtain the displaced volume $V_\infty = uS_1$, the seismic moment of the impact $M_0 = \rho c_P^2 uS_1$, and the seismic energy $E_s = 0.75\sigma_s uS_1$.

The seismic efficiency for an impact is defined by

$$k_s = \frac{2E_s}{mv_i^2} = C_1\eta\Big(1 + 0.2\sqrt{\frac{\rho_p}{\rho_t}}\Big)\Big(\frac{\sigma_s}{\mu}\Big)^2 \frac{\mathrm{Fr}^{0.66}}{\mathrm{M}_i^2}, \tag{3.2}$$

where $C_1 = 1.4$, $\eta = (\sqrt{1-\varepsilon^2} + \arcsin(\varepsilon)/\varepsilon)$, $\mathrm{M}_i = v_i/c_P$ is an analog of the Mach number, and $\mathrm{Fr} = v_i^2/(gL)$ is an analog of the Froude number.

We introduce the parameter $\alpha_t = gL_t/c_P^2$ (L_t is the diameter of the target planet). Then, formula (3.2) can be written as

$$k_s = C_1\eta\Big(1 + 0.2\sqrt{\frac{\rho_p}{\rho_t}}\Big)\Big(\frac{\sigma_s}{\mu}\Big)^2 \frac{1}{\mathrm{M}_i^{0.68}}\Big(\frac{L_t/L}{\alpha_t}\Big)^{0.66}$$

$$\approx C_1\eta\Big(1 + 0.2\sqrt{\frac{\rho_p}{\rho_t}}\Big)\Big(\frac{\sigma_s}{\mu}\Big)^2 \Big(\frac{L_t/L}{\alpha_t \mathrm{M}_i}\Big)^{2/3}. \tag{3.3}$$

Relation (3.3) implies that the SE of an impact on a particular planet decreases as $(\mathrm{M}_i L)^{-2/3}$ with increasing impact velocity and impactor dimensions. Since for terrestrial planets, the Mach number and the strength parameter σ_s/μ vary in a rather narrow range (by approximately an order of magnitude), the impactor dimensions have the main effect on the SE of an impact. Therefore, the SE of an impact varies over a very broad range. The values of the parameter α_t are given in Table 1.

In the case of aerolite impact ($\rho_p/\rho_t \approx 1$, $\varepsilon = 0.97$, $\arcsin\varepsilon = 1.33$, and $\eta = 1.65$), formula (3.3) is simplified:

$$k_s = 2.8\Big(\frac{\sigma_s}{\mu}\Big)^2 \Big(\frac{L_t/L}{\alpha_t \mathrm{M}_i}\Big)^{2/3}. \tag{3.4}$$

TABLE 2

Seismic Efficiency k_s of a Meteorite Impact on the Earth

L, km	L_t/L	k_s	
		$\mathrm{M}_i = 1$	$\mathrm{M}_i = 12$
1	$1.276 \cdot 10^4$	$7.0 \cdot 10^{-3}$	$0.30 \cdot 10^{-3}$
10	$1.276 \cdot 10^3$	$1.5 \cdot 10^{-4}$	$2.90 \cdot 10^{-5}$
100	$1.276 \cdot 10^2$	$3.2 \cdot 10^{-5}$	$0.65 \cdot 10^{-5}$
1000	$1.276 \cdot 10^1$	$7.0 \cdot 10^{-6}$	$1.40 \cdot 10^{-6}$

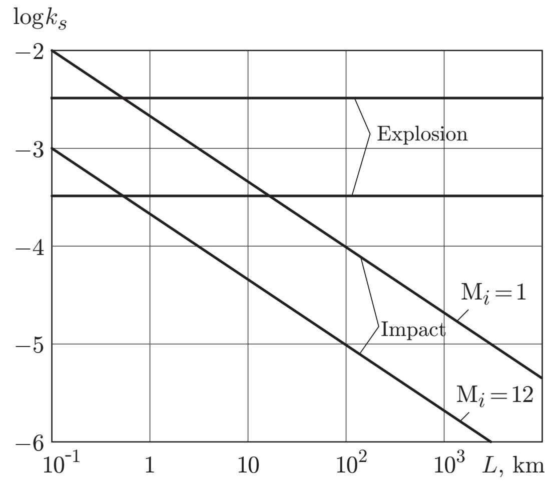

Fig. 4. Seismic efficiency of a contact explosion and an impact on a planet's crust for $\sigma_s/\mu = 10^{-3}$.

We determine the SE of a meteorite impact on the Earth. The velocities of the meteorites approaching the Earth are in the range from 12 km/sec (overtaking impact) to 72 km/sec (meeting impact) [16]. In view of atmospheric braking, the corresponding Mach numbers can have values of 1 to 12. The relative strength of the Earth's crust is $\sigma_s/\mu \approx 10^{-3}$. Table 2 gives SE values calculated by formula (3.4) for various diameters of meteorites and limiting values of the Mach number.

Figure 4 gives curves of $k_s(L)$ for an impact and explosion, from which it follows that the SE of an impact of a meteorite of diameter $L = 1$–50 km can be higher than that of a contact explosion. If the meteorite diameter $L > 50$ km, the SE of its impact on the Earth is smaller than that of an explosion.

Let us estimate the SE of an impact effect capable of forming a crater equal to the crater of the Sea of Rains on the Moon. The impact parameters are calculated in [17]. An iron meteorite of diameter $L = 35$ km impacts the Moon surface at a velocity $v_i = 15$ km/sec. The material of the Moon crust is gabbroic anorthosite with parameters $\rho_t = 2940$ kg/m^3, $g = 1.62$ m/sec^2, $\alpha_t = gL_t/c_P^2 = 0.31$, $c_P = 5000$ m/sec, $\gamma = c_S/c_P = 0.58$, and $\sigma_s/\mu = 2.4 \cdot 10^{-3}$ (the last three parameters are estimates of the author). Using the above formulas, we obtain $k_s = 10^{-3}$. The seismic efficiency of a contact explosion with an energy equal to the kinetic energy of the meteorite would have the value $k_s = 10^{-4}$–10^{-3}.

Conclusions. The seismic efficiency of contact explosions and meteorite impacts on a planet depends on the scale of fracture of the crust rock and the volume of the medium displaced into the elastic-strain region. Its value increases with increasing strength of the crust material and decreases with decreasing meteorite dimensions and velocity. For a relatively weak impact, its SE is higher than the SE of a contact explosion of comparable energy, and for a relatively strong impact, it is lower than the SE of a contact explosion of comparable energy. The seismic efficiency of meteorite impacts varies over a wide range from the value $k_s \approx 10^{-2}$ for relatively weak impacts ($L/L_t \leqslant 10^{-5}$ and $\mathrm{M}_i \approx 1$–2) to the value $k_s \approx 10^{-6}$ ($L/L_t \geqslant 10^{-5}$ and $\mathrm{M}_i \approx 12$) for very strong impacts.

The decrease in the SE of an impact with increasing kinetic energy of the impactor is due to two main factors: the gravity on the planet and the strength of the crust. An increase in the kinetic energy due to an increase in the meteorite dimensions results in an increase in the work expended in overcoming gravity in the crater-forming flow process. This leads to a relative decrease in the diameter of the transient crater, the adjacent region of fractured rock, residual displacements, the surface area of the fracture region, the displaced volume, and the SE.

It should be noted that the above estimates of the SE are not fairly accurate. Contact explosions and impacts generate both longitudinal and transverse waves. The method of estimating the SE described above ignores the contribution of transverse waves. The transverse-wave energy is of the same order of magnitude as the longitudinal-wave energy. In addition, one should take into account the contribution of the waves generated by impact of ejections on the planet's surface. However, an impact of the ejected rock on the planet's surface cannot impart it an energy higher than the seismic energy imparted by the impactor. Therefore, the increase in the SE due to the impact of ejections cannot exceed the value given by formulas (3.2) or (3.3). Thus, the total increase in the SE (taking into account the energy of transverse elastic waves and the waves generated by the impact of ejections) should not change the order of the quantity SE estimated in the present work.

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