About explosive technology of building road embankments, tunnels, canals

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Abstract
Performing different works (construction of road embankments, canals, tunnels, moving some soil mass in a given direction), as well as construction of various towers, power transmission supports, foundations for bridge supports, special pits for anchors is carried out by explosive technologies. When carrying out excavation works related to the construction of road embankments, trenches, wells, cord charges are used. From the mathematical point of view, the calculation of such charges presents the problem of determining the movement of soil particles in the plane perpendicular to the axis of the corded charge. Calculation of geometrical characteristics of the above construction works is based on impulse-hydrodynamic setting, having "liquid" and "solid-liquid" varieties. The work gives two examples of calculations within both productions. In the first problem, within the framework of the solid-liquid model, the entire boundary of the channel is determined in the case of an explosion of a square charge, while in the second problem the explosion of two charges, when there is a circular cylinder in the ground, is investigated.

Keywords: road embankments, canals, explosive technologies, cord charges, impulse, complex potential

1 Introduction
The energy of an explosion is a special type of energy that can be easily metered, its transfer does not require stationary communications, and its ability to perform work eliminates the need for complex working machines. Its high concentration and enormous power characteristics have also determined the special field of use of the energy of explosion, where other energy sources are ineffective.

Explosive technologies have found wide application at development of mineral resources [1, 2], at consolidation of grounds [3, 4], they are used at reception of underground tanks [5, 6], in tests of building designs on impulse influence [7]. At manufacture of some works (building of road embankments, channels, foundation pits) there is a task of moving of some weight of a ground in the set direction. Construction of various towers, power transmission towers, foundations for bridge supports, special foundation pits for anchors and their concreting is carried out using explosive technologies. During excavation works related to the construction of road embankments, trenches and wells, so-called cord charges are used, as a rule, which are kapron hoses filled with explosives. The implementation of these construction works often proved to be effective as proposed by M.A. Lavrentyev’s impulse-hydrodynamic model for the study of the explosion, the essence of which is as follows. As experiments show, the movement of the medium accompanying the explosion can be divided into two stages. The first, short-term, is characterized by the propagation of the stress wave and a relatively small increase in displacements and velocities of the particles. At this stage, reflections may occur and destruction may occur.

Many works have been devoted to the study of the first stage of the explosion associated with the detonation of charges [8, 9], the structure of shock waves [10-13], as well as the spread of shock waves [14-18].

The second stage is ballistic. There is either non-camouflage explosion or individual blocks are thrown away from the point of explosion. The study of the second stage is of interest not only in the construction, but also in the study of the formation of craters of celestial bodies [19-21]. At the end of
the first stage, a velocity field "initial" for the ballistic stage is produced. In the first stage, the fields of stress and velocity are determined mainly by the inertial resistance of the medium, so the compressibility can be neglected. Since the pressure at the initial stage of the explosion is very high, a second assumption is made to consider the strength effects as secondary and to describe the state of the ball pressure tensor. All this makes it possible to assume that the medium is incompressible, that the medium is ideal (that is, there are no tangential stresses), and that deformations and displacements remain small. These assumptions make it possible to use the model of an ideal incompressible fluid to calculate the size, embankment, tunnel or trench when calculating the explosion for an ejection. M. A. Lavrentyev introduced an additional strength characteristic of the soil - critical velocity.

Built by Lavrentyev M. A., the model is called impulse-hydrodynamic and consists in the following. Due to the large magnitude of the explosive loads and the short duration of their action at the initial stage of the explosion medium can be considered an ideal incompressible liquid, then its movement is described by the equation.

\[ \frac{d\vec{v}}{dt} = -\nabla p/\rho \]

or \( dv \vec{v} = 0 \), where \( \vec{v} \) - vector of velocity, \( t \)-time, \( p \)-pressure, \( \rho \)-medium density, \( \nabla p = gradp \).

If we apply the impulse model of problems of hydromechanics, then we can obtain the field velocity through potential.

\[ \vec{v} = \nabla (\frac{-P}{\rho}) = \nabla \varphi \], where \( \varphi = -P/\rho \) - potential of speed, \( P = \int_0^t p(t)dt \), \( P \)-impulse of pressure, and for \( \varphi \) we have \( \Delta \varphi = 0 \) (A - Laplace operator), i.e. \( \varphi \) function is harmonic.

In the case when the velocity field is flat (tasks about the explosion of cord charges), the complex current potential \( w(z) = \varphi(x, y) + i\psi(x, y) \) (a current function complexly connected to \( \varphi(x, y) \), which is an analytical function of the complex coordinate \( z = x + iy \), and its derivative has the form \( \omega = \frac{dw}{dz} = \nu_x - i\nu_y = ve^{-i\theta}(\nu, \theta, \nu_x, \nu_y \) - correspondingly the value, argument and components of the velocity vector) and is called complex velocity.

There are various varieties of impulse- hydrodynamic model. In one of them, called the "liquid" model the ground is considered as an ideal incompressible fluid in all the occupied area. According to this model, the edge of the excavation is defined as a point on a free surface where the velocity is equal to some critical value \( v^* \), called critical velocity. However, in the framework of the liquid model, the question of finding the entire edge of the ditch of the ejection remains open. In another "solid-liquid" model, the ground is described by the equations of ideal incompressible liquid, only in some area near the charge. Outside of this area, the soil behaves like an absolutely rigid body, the boundary separating the liquid is a solid wall, which is located from the condition that the velocity module on it is equal to a critical value. The critical velocity is a strength characteristic of the medium and is defined as follows. Fracture is considered to occur when the specific kinetic energy of the medium particles \( e = \rho v^2/2 \) exceeds the limit specific energy \( e_* = \sigma^2/2E \) required for the destruction of the medium (here \( E \)-Young's module, \( \sigma_* \)-yield strength limit). Then from the condition \( e = e_* \), critical velocity can be found by formula \( v^* = \sigma_*/\sqrt{\rho E} \).

2 Methods

For the solution of explosion problems in impulse-hydrodynamic statement the methods of the theory of functions of complex variable are used, in particular, the theory of boundary problems of analytic functions [22-25], having wide application in the theory of explosion [26, 27] and in hydrodynamics [28, 29].

Let's consider a problem about the explosion of infinitely long buried cylindrical charge of square section within the limits of solid-liquid model. According to this model, only a part of the ground near the charge moves during the explosion, and it behaves like an ideal incompressible liquid. As the movement of the liquid is plane-parallel, it is enough to study it in the plane perpendicular to the forming cylindrical surface limiting the charge. This plane can be described by the complex variable
z = x + iy. Let’s direct the real axis along the plane coinciding with the surface of the earth, the charge will be read in the semi-plane y < 0. The liquid flow is described by the complex potential \( w(z) = \varphi(x, y) + i\psi(x, y) \).

The tops of the square, which is a cross-section of the charge of the z plane, denote M, N, E, K and accept that they follow in the specified order when bypassing the square counterclockwise, and the vector MN with the real axis forms the angle \( \alpha \), \( 0 \leq \alpha < \pi/2 \). The area of current from above is limited by the segment C, C of the real axis, and the abscises of these points satisfy the condition \( x_c, < x_c \) (in the future, everywhere the coordinates of that or other point will be supplied with a letter denoting the point), and from below is limited by the line C, DC, representing the current line with the branching point D, in addition, on line C, DC the speed value remains constant and equal to critical \( v_0 \).

Let \( \omega = \frac{d\varphi}{dz} = \exp(-i\theta) = v_\tau - iv_\sigma \) be the complex velocity of the flow. On the border of the square and in the section C, C the potential of the speed \( \varphi = \text{const} \). On them, the velocity vector \( \exp(i\theta) \) is perpendicular to the specified sections. Taking this into account, it is not difficult to show that in points M, N, E, K the velocity value \( \nu \) turns to infinity.

Let \( A_1, A_2, A_3, A_4 \) be the essence of the point of the segments, respectively MN, NE, EK, KM, at which the velocity \( v \) as a function of the points of these segments reaches a minimum, and A be the point of the segment C, C, at which the velocity \( v \) as a function of the points of this segment reaches maximum.

The flow area in the plane \( \omega \) correspond to the area bounded by the circle \( |\omega| = \nu \), the banks of the section along the segment connecting the points \( \omega = -i\nu, \omega = -i\omega_4 \) and the banks of straight cuts, from the points \( \omega_{A_1}, \omega_{A_2}, \omega_{A_3}, \omega_{A_4} \) to the infinitely distant point (corresponding points in different planes are marked with the same letters).

Let’s denote the flow area through \( G_z \). In the area \( G_z \) we make a cut along the current line from the point of flow branching \( D \) to \( L \), lying on the segment MN. Right and left banks of the section shall be marked \( D_2L_2 \) and \( D_1L_1 \) respectively. And for the function \( w(z) \) we have the following boundary conditions: \( \varphi = 0 \) in C, C; \( \varphi = -\varphi_0 (\varphi_0 = \text{const} > 0) \) in \( L_1M Ken L_2 \), where \( -\varphi_0 \) is the value of the potential of speed on the charge; \( \psi = 0 \) on \( C, D_1 L_1; \psi = \psi_0 = \text{const} > 0 \) in \( L_2 D_2 C \) (\( \psi_0 = \text{const} > 0 \)). Also on sections \( C, D_1 \) and \( D_2 C |dw/dz| = \nu \).

The task is to determine the \( C, DC \) curve, i.e. the shape of the ejection dug for given \( \varphi_0, \nu \), in an explosion of the specified charge.

Let’s enter the plane of the auxiliary complex variable \( u = u_1 + iu_2 \) and take the rectangle \( G_u \) with its vertices at \( 2\omega_1, 2\omega_1 + i\omega_2, i\omega_2, 0 (\omega_1 > 0, \omega_2 > 0) \). Let the outer boundary of the two-linked area \( G_u \) correspond to the lower base of the rectangle, and the inner boundary corresponds to the upper base. Let the points \( D_3, D, C, D_4, L_1, M, E, N, L_2 \) of the boundary in the area \( G_z \) correspond to the point \( 0, c, c, 2\omega_1, 2\omega_1 + i\omega_2, m + i\omega_2, k + i\omega_2, e + i\omega_2, n + i\omega_2, i\omega_2 \) of the rectangle \( G_u \).

Let’s introduce the analytical function \( z(u) = x(u_1, u_2) + iy(u_1, u_2) \) in rectangle \( G_u \), which conformally displays this rectangle in the \( G_z \) region.

Since lines \( C, D_1 \) and \( D_2 C \) are current lines, then \( (dy/\partial u_1)/(|dx/\partial u_1|) = tg\theta \) or
\[
\cos\theta \left( \frac{\partial y}{\partial u_1} \right) - \sin\theta \left( \frac{\partial x}{\partial u_1} \right) = 0 \quad (0 < u_1 < c, \quad c, < u_1 < 2\omega_1),
\]
where \( x = x(u_1, 0), y = y(u_1, 0) \). In the \( CC \) section, we have \( \frac{\partial y}{\partial u_1} = 0, c < u_1 < c \). In the sections \( L_1 M, KE, NL_2 \) we get
\[
\cos\alpha \left( \frac{\partial y}{\partial u_1} \right) - \sin\alpha \left( \frac{\partial x}{\partial u_1} \right) = 0, (m < u_1 < 2\omega_1, c < u_1 < k, 0 < u_1 < n).
\]
Finally, in the \( KM \) and \( NE \) sections we have
\[
\sin\alpha \left( \frac{\partial y}{\partial u_1} \right) + \cos\alpha \left( \frac{\partial x}{\partial u_1} \right) = 0, (k < u_1 < m, \quad n < u_1 < e).
\]
Thus, we have come to the task of constructing the analytic function in the \( G_u \) rectangle \( \partial x/\partial u_1 = \partial x/\partial u_1 + i\partial y/\partial u_1 \) by the boundary condition
\[ \alpha(u_1) \partial x/\partial u_1 + b(u_1) \partial y/\partial u_1 = 0, \]

where

\[ \alpha(u_1) = \begin{cases} -\sin \theta, b(u_1) = \cos \theta \alpha \theta & < c, c < u_1 < 2\omega_1, \\ 0, b(u_1) = 1 & c < u_1. \end{cases} \]

It is not difficult to check that the solution of the obtained homogeneous Hilbert problem should be searched for in the class of functions that are unlimited near the points \( C, C \) limited near the points \( M, K, E, N \) and turn to zero of the first at the point \( u = 0 \).

Let us represent the \( dz/du \) function as

\[ \frac{dz}{du} = \sigma(u)g(u), \]

where \( \sigma(u) \)-sigma-function of Weierstrass built for the periods \( 2\omega_1, 2i\omega_2, g(u) = \mu(u_1, u_2) + iv(u_1, u_2) \)-function limited in the points \( M, K, E, N \) and in the points \( C, C \) has the feature of half order. At \( u_2 = 0 \) of (1) we get

\[ \partial x/\partial u_1 + i\partial y/\partial u_1 = \sigma(u_1)(\mu(u_1) + iv(u_1)). \]

From here it is easy to get the boundary conditions for the function \( g(u) \) on the \( l_1 \) side of the rectangle in the form of

\[ \alpha(u_1) \mu(u_1) + b(u_1) \nu(u_1) = 0, \]

where

\[ \alpha(u_1) = -\sin \theta, b(u_1) = \cos \theta \] at \( 0 < u_1 < c, c < u_1 < 2\omega_1, \alpha(u_1) = 0, b(u_1) = 1 \) at \( c < u_1 < c. \]

On the \( l_1 \) side, we have

\[ z^*(u_1 + i\omega_2) = \sigma(u_1 + i\omega_2)(\mu + iv)(u_1 + i\omega_2) = (\exp \psi_2)\sigma(i\omega_2)\sigma(u_1)(u_2) = \text{Weierstrass functions}. \]

Expressing from here \( \frac{\partial x}{\partial u_1}, \frac{\partial y}{\partial u_1} \) through \( \mu \) and \( \nu \) we get the edge condition for the function \( g(u) \) in the form of (2), where

\[ \alpha(u_1) = r_2 \cos a - r_1 \sin a, \quad b(u_1) = r_1 \cos a + r_2 \sin a, \]

\[ \text{at} \quad k < u_1 < m, \quad n < u_1 < e. \]

In accordance with what was said for the Hilbert task, we will take the following branches: \( \tilde{\theta}(u_1) = \arg \left( \frac{\sigma(u_1 + i\omega_1)}{\sigma(u_1 - i\omega_1)} \right), \tilde{\theta}(u_1) = 2\theta - \pi \text{ on } D_2; \tilde{\theta}(u_1) = 2\theta + 5\pi \text{ for } C, D; \tilde{\theta}(u_1) = 2\alpha + 2\beta - \pi \text{ for } MK; \tilde{\theta}(u_1) = 2\alpha + 2\beta \text{ for } L_2; \tilde{\theta}(u_1) = 2\alpha + 2\beta - 3\pi \text{ for } EN; \tilde{\theta}(u_1) = 2\alpha + 2\beta \text{ for } N_2. \]

The angle \( \beta \) is determined from the ratio \( r_1 / \sqrt{r_1^2 + r_2^2} \). Here, the angle \( \beta \) is determined from the ratio \( r_1 / \sqrt{r_1^2 + r_2^2} \).

The index of Hilbert task \( \chi = \chi_1 + \chi_2 = 1 \) where \( \chi_1 = 3, \chi_2 = -2. \) This case is \( \chi_1 + \chi_2 = 1, \chi_1 = 2, \chi_2 = -1. \) From formula [23] we have

\[ X(u) = \exp (\Gamma(u)) [\sigma(u)]^{-4}[\sigma(u - i\omega_2)\sigma(u + i\omega_2)][\sigma(u - \bar{u}_2)\sigma(u - \bar{u}_1)]. \]

The solution of the Hilbert problem is defined by the formula \( g(u) = X(u)\psi(u) \), in which

\[ \psi(u) = ReC - i(ImB_0^*)\zeta(u - u_2) + i(ImB_0^*)\zeta(u - \bar{u}_2), \]

and \( B_0 + B_0^* = 0. \) The real condition \( \psi(0) = 0, \) that is \( ReC = -i(ImB_0^*)\zeta(u_2) + i(ImB_0^*)\zeta(u) \) is the safe choice of \( ReC. \)

Using the function \( z(u) = \sigma(u)g(u) \) let's find the function

\[ z(u) = \int_u^\mu \alpha(u)g(u)du, \]

giving a conformal mapping of \( G_u \) to \( G_y. \) There should be \( z(0) = z(2\omega_1), \) that two real equations give. Besides, according to the condition \( |NM|=|KM| \) and the latter conditions represent a system of nonlinear equations, questions of existence and uniqueness of their solution require special
consideration. Moving to (3) to the limit by Sokhotsky's formulas, we obtain the boundary equation of $G_2$ region.

2. Second example. We study an explosion problem for two pinching charges in a homogeneous medium with a circular cylinder lying in the flow caused by the explosion. We assume that, in the plane $\vec{z} = \vec{x} + i\vec{y}$ perpendicular to the axes of the charges, the charges are simulated by dipoles with moments $M_0$ and $M_1$, lying on the free $\vec{y} = 0$. In this case we use the impulse -hydrodynamical model [26, 27].

Within the framework of this model, the fluid behaves as an ideal incompressible fluid in the entire region filled this fluid, and the motion is plane -parallel. We assume that the axis $\vec{x}$ is the free surface where the charges simulated by dipoles lie at the points $\vec{x}_0$ and $\vec{x}_1$. So, a cylinder of radius $a_0$ is given; its axis lies at the depth $h$ ($h > a_0$) from the surface.

We introduce the complex potential $\vec{w}(\vec{z}) = \phi(\vec{x}, \vec{y}) + i\psi(\vec{x}, \vec{y})$, which must satisfy the following boundary conditions: $\phi = 0$ on the axis $\vec{x}$ and $\psi = 0$ on the boundary of the disk. Near the points $\vec{z}_0 = \vec{x}_0$ and $\vec{z}_1 = \vec{x}_1$, we have

$$\vec{w}(\vec{z}_1) \approx \frac{iM_1}{2\pi(\vec{z} - \vec{z}_1)}, \quad \vec{w}(\vec{z}_0) \approx \frac{iM_0}{2\pi(\vec{z} - \vec{z}_0)},$$

where $M_0$ and $M_1$ are the dipole moments.

We map the flow domain onto the annulus $q < |z| < 1$ by using the function

$$z = \frac{(x+i\sqrt{h^2-a_0^2})}{(x-i\sqrt{h^2-a_0^2})}. $$

The radius $q$ ($q < 1$) of the smaller circle is equal to

$$q = \frac{(\sqrt{h+a_0}+\sqrt{h-a_0})}{(\sqrt{h+a_0}-\sqrt{h-a_0})}. $$

This mapping assigns the circle $|z| = 1$ to the axis $O\vec{x}$, the point $t_0$ to the point $x_0$ and the point $t_1$ on the circle $|z| = 1$ to the point $x_1$. Thus we obtain Hilbert's problem $a(t)\phi(t) - b(t)\psi(t) = c(t)$ for an annulus. Herewe have $a = 1$, $b = 0$, and $c = 0$ for $|z| = 1$, $a = 0$, $b = -1$, and $c = 0$ for $|z| = q$, or the condition

$$Re[(a + ib)\vec{w}] = 0. \quad (4)$$

We represent $\vec{w}(z) = w_1(z)/((z - t_0)(z - t_1))$, where $w_1(z)$ is a function single -valued and analytic in the annulus $q < |z| < 1$. We rewrite condition (4) in the form

$$Re\{exp(-i\nu(t) + arg(t - t_0) + arg(t - t_1))w_1(t)\} = 0,$$

where $\nu(t) = arg(a - ib)$.

Just as before, we introduce the function $\phi_1(t) = \nu(t) - \beta(t)\pi$ and choose the function $\beta(t)$ so that $-\pi < \nu_1(t_j + 0) - \phi_1(t_j - 0) \leq 0$ for $0 \leq j \leq 1$, since the function $w_1(t)$ is bounded at the points $t_0, t_1$.

Here we can verify the fact that $N_0 = N_1 = 0, m_0 = 2, m_1 = 0$. This means that the index of the problem is $\mathcal{N} = 2$, and moreover, $\mathcal{N}_0 + m_0 = 2$ and $\mathcal{N}_1 = 0$. Hence we can use the results obtained in [22].

Thus the solution is determined by the formula

$$\vec{w} = \frac{(x-z_1)exp(\Gamma(z))}{(x-t_0)(x-t_1)} \left\{S(\vec{c}_1, z) + iC_0 + \frac{v + iv}{x-z_1} \right\}, \quad (5)$$

where

$$\vec{c}_1 = c_1(t) - Re \frac{v + iv}{t-z_1} = -Re \frac{v + iv}{t-z_1}$$

In this case we have

$$v = \frac{r}{2\pi} \int \frac{c_1(t)}{it} dt = v\coth a,$$

i.e. $v = -v\coth a$. 

\[ \Gamma(z) = iS(\psi, z) = \frac{i}{\pi^2} \int \psi(t) \left[ \frac{\omega \eta Z}{\pi i} \right] \frac{1}{t} dt. \]

\[ \psi(t) = \varphi(t) + \theta(t) - \arg(t - z_1) + \sigma(t) \eta. \]

After the complex potential (5) is calculated, we can readily find all desired characteristics in the physical plane.

3 Results and Discussion

The use of force is widespread in building technologies [30].

The work analyzes the use of explosive technology in various fields of activity, shows the successful use of explosion energy in the construction industry, especially related to explosions for release. The calculation of explosions is a complex task that requires the use of advances in shock wave theory, detonation, and solid media mechanics. However, detonation as a section of technology requires simple schemes for calculating explosions. Impulse-hydrodynamic statement is convenient from this point of view and allows the methods of marginal problems of the theory of analytical functions to obtain accurate solutions to problems to determine the boundaries of the ejection. In the work within the framework of two varieties of impulse-hydrodynamic statement two explosion problems are solved, for which the formulas allowing to find geometrical and physical parameters of the ejection notch are obtained.

4 Conclusion

In the process of construction of road embankments, canals and foundation pits there is a problem of moving some soil mass in a given direction and calculating the geometry of channels and foundation pits. Such works are often carried out with application of explosive technologies, thus cord charges are often used. For calculation of geometrical characteristics of excavations at explosion of such charges it is possible to use analytical methods within the limits of pulse-hydrodynamic statement. In the work two problems of explosion are solved: a cord charge of square section; two cord charges in a homogeneous medium when it has a circular cylinder. In the study, calculated schemes are established and simulation of the process of formation of the ditch (trench, channel) is carried out, geometric and physical parameters affecting the shape and size of the ditch are determined, formulas for finding in the physical plane of all the interesting features of the ditch are obtained.

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