Journal of Applied Mechanics and Technical Physics, Vol. 40, No. 3, 1999

GAS-DYNAMIC METHOD OF DECREASING THE FORCE OF PENETRATION OF A SOLID INTO GROUND

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UDC 534.222.2

A new gas-dynamic method for decreasing the resistance of ground to the penetration of a solid body is developed. The physical essence of the process is considered. Theoretical fundamentals of scaled modeling are given. Results of experimental studies are presented, and the range of parameter for which the method is effective is determined.

The phenomenon of penetration of a body into ground is frequently considered from the viewpoint of practical uses. This is due to the necessity of installing piles and supports, laying service lines, etc. Special technologies and technical means have been designed to solve these problems.

From the viewpoint of physics, the most important feature of the process of penetration is the character of overcoming of the ground resistance: dynamic or static. According to [1], the resisting force in the dynamic penetration of a body into ground is generally described by the relation

$$F = AU^2 + BU + C,$$

where U is the penetration rate. The first component of the resistance A, proportional to the square of the penetration rate, is due to the inertial effects in the ground and unsteadiness of the process. The second component B is determined by the viscous effects of the medium, and the third component C is the force of counteraction of the medium in the static penetration of the body. Apparently, from the viewpoint of the rational use of power resources, the regime of static (quasistatic) penetration of a body into ground is most reasonable. Therefore, we shall consider precisely the static regime.

The present paper is devoted to further searches for methods of decreasing the head penetration resistance. The solution of this problem involves the use of the previously designed pulsed gas-dynamic method of displacing loose materials by applying a series of pulses from deep sources to a mass of loose material [2]. Displacement is possible with formation of both ejection cavities and camouflet cavities in the material. The sources operate in the regime of a "traveling wave," and the displacement wave of the loose material is opposite in direction. In the present paper, we consider the regime of motion with formation of camouflet cavities.

The key features of the process of penetration with a decrease in the mechanical drive force by a gas-dynamic method are shown in Fig. 1. The head of the axisymmetric body of revolution has a device for dosing gas pulses 1, designed to generate successive gas pulses of specified duration and feed them to several gas collectors 2. Each collector has a series of orifices 3 located on the surface of the header 4 of the body of revolution in one section relative to the longitudinal axis. Pulsed feeding of the gas to the collectors ensures delivery of the gas-dynamic pulses from the orifices to the adjacent ground.

The physical essence of the evolution of fragments of the ground is determined by the order of generation of gas pulses. Thus, operation of the ith collector produces a series of camouflet cavities in the surrounding mass, which merge to form a tore space. The formation of each cavity is accompanied by packing of ground particles and their displacement in the radial direction relative to the longitudinal axis of the penetrating body, i.e., toward the line of penetration. Next, after a delay, pulsed feeding of gas to the $(i + 1)$th collector

Mozhaiskii Military Space-Engineering Academy, St. Petersburg 197082. Translated from Prikladnaya Mekhanika i Tekhnicheskaya Fizika, Vol. 40, No. 3, pp. 196–199, May–June, 1999. Original article submitted June 23, 1997.

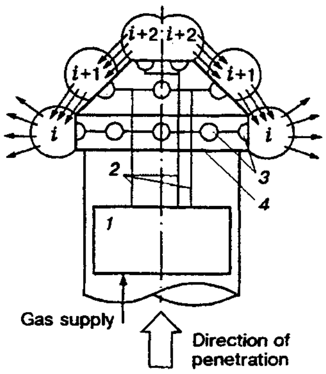

Fig. 1. Kinematics of penetration of a solid body into ground and gas-dynamic displacement of the ground from the line of penetration.

follows. As a result, a new tore space forms, and the ground mass lying between the spaces moves, filling the previous space formed by the gas pulse from the ith collector. Then, the $(i+2)$th collector generates a pulse, etc. Thus, when the body continuously penetrates at constant speed into the mass, an additional mechanism of packing and radial displacement of the ground from the line of penetration is realized.

Experimental studies were performed using dried quartz sand with 1.5 mass % additive of vacuum oil [3] as a model ground. The header of the body of revolution was 0.07 m in diameter, the ith and $(i+1)$th rows each contained 6 orifices, and the $(i+2)$th row contained 3 orifices.

As the major factors determining the mechanics of development of the process, we considered the following dimensionless parameters.

By analogy with [2], the total energy of the gas in a single gas-dynamic pulse from one orifice is described by

$$\bar{E}_\Sigma = \frac{E_\Sigma}{(P_\gamma + P_a)a^3},$$

where a is the characteristic distance that corresponds to the distance between the rows of sources on the head of the penetrating body (in our case, $a = 0.02$ m), and E_Σ is the total work of gas-dynamic ejection with allowance for the gas expansion from the gas pressure in the source P to the ambient pressure, determined by the sum of atmospheric pressure P_a and rock pressure P_γ; it is calculated from the formula

$$E_\Sigma = \frac{PV}{k-1}\left[1 - \left(\frac{P_a + P_\gamma}{P}\right)^{(k-1)/k}\right].$$

Here V is the gas volume ejected in a pulse and k is the adiabatic exponent.

The second determining factor of the process — the delay of operation of the sources of the next collector — is defined, as in [2], by

$$\bar{T}_{\rm d} = \frac{T_{\rm d}}{a}\sqrt{\frac{P_\gamma + P_a}{\rho}},$$

where $T_{\rm d}$ is the absolute value of the delay and ρ is the ground density.

The third determining factor — the packing density of the ground mass — depends on the type of ground and the depth at which the process occurs. According to [4], its value is determined by the packing density index:

$$\bar{I}_d = \frac{\rho_{\max}(\rho_i - \rho_{\min})}{\rho_i(\rho_{\max} - \rho_{\min})},$$

where ρ_i, $\rho_{\max}$, and $\rho_{\min}$ are the current and maximum and minimum possible densities of the ground.

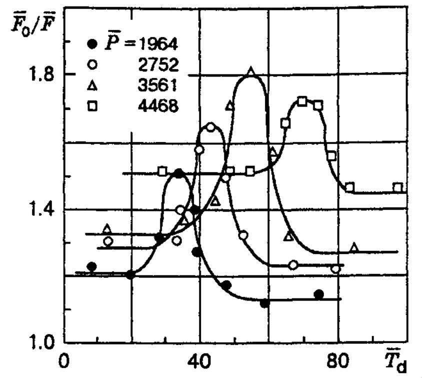

Fig. 2. Force of penetration of the body into ground $\bar{F}_0/\bar{F}$ versus the delay between the operation of sources of gas energy $\bar{T}_d$ at $\rho = 1490$ kg/m^3, $\bar{I}_d = 0.5$, and $\bar{E}_\Sigma = 0$–5.

The rate of penetration of the body U is obtained from the condition that the kinetic energy of the ground displaced from the ejection line is proportional to the value of $\rho u^2 a^3$, where u is the rate of motion of the ground mass at the surface of the head of the body. From the ratio of the kinetic energy of motion to the scaled value of the total energy of gas-dynamic ejection, we obtain

$$\bar{U} = u\rho^{0.5}/\sqrt{P_\gamma + P_a}.$$

The penetrating force was defined as the ratio of its absolute value F to the rock pressure at a certain depth: $\bar{F} = F/P_\gamma$. The penetrating force without gas feeding is denoted by the variable $\bar{F}_0$.

The effect of rock pressure was modeled by additional loading of the quartz sand used in the investigation and by preliminary packing of it with a specified density, which was obtained by layer-by-layer (by 0.04 m) pouring of the sand and loading it by a stamp of a specified mass.

The range of the total energy of gas-dynamic ejection from one orifice in the head was $E_\Sigma = 0.2$–4.1 J, the delay of operation of the next sources was $T_d = 0.03$–0.23 sec, the ground density index was $\bar{I}_d = 0$–0.86 for an absolute density of the mass of quartz sand of $\rho = 1350$–1600 kg/m^3, and the rate of penetration of the body was $u = 0.005$–0.006 m/sec.

The results of the experimental studies of the process show that there is a distinct, rather narrow range of parameters which ensures a considerable (by a factor of about 1.7–1.8 times) decrease in the penetrating force. Characteristic curves of the penetrating force versus the delay for several values of the gas charge pressure $\bar{P}$ are given in Fig. 2. The total energy of the gas ejected in a pulse was specified by the duration of opening of the ith collector in the section device. The curves show that this effect of decrease in the penetrating force is most pronounced for the regime of displacement of the mass involving production of camouflet cavities.

For low energy of gas-dynamic ejection, displacement of the mass does not occur and the insignificant feeding of the gas from the head is responsible for the regime of pseudo-liquefaction of the mass. This somewhat decreases the penetrating force. An increase in the rate of feeding of the gas leads to growth of camouflet cavities, which at particular distance between the sources ensure the evolution of the mass. The penetrating force in this case decreases considerably. With further increase in the amount of the fed gas, the dimensions of camouflet cavities increase so that the gas sources of neighboring gas collectors fall in the limits of these cavities. Successive operation of these sources results in gas ejection inside the previous camouflet cavities, which does not cause displacement of the mass. The penetrating force increases in this case. However, this force is somewhat weaker than the force corresponding to the smaller amount of the fed gas. This is explained by the higher intensity of development of pseudo-liquefaction.

The following physical feature of the process should be noted. When a body penetrates with gas feeding from the head, both effective and neutral stresses in the mass exert penetration resistance [5]. The effective stresses are caused by the counteraction of the ground mass as an aggregate of nondeformable particles, and the neutral stresses are due to the pore gas pressure. Therefore, pulsed feeding of the gas from the head of the penetrating body [in the particular experiment performed, from the orifices of the $(i+2)$th collector] causes a certain pulsed increase in the counteraction of the ambient medium to the rod of the mechanical drive. The fraction of this force does not exceed 5%.

Analysis of the curves and the quantitative results obtained on a computer using the least-square method yields the following empirical formula, which agrees with an accuracy of 20% with the experiment:

$$\frac{\bar{F}_0}{\bar{F}} = 0.9\,\frac{(1+0.01\bar{E}_\Sigma)^{1.5}}{(1+0.01\bar{E}_\Sigma^{1.5})\exp(0.8I_d \ln I_d)}\,[1+\bar{T}_{\rm d}^{0.01}\exp(-0.1\bar{T}_{\rm d}^{0.01})].$$

The gas-dynamic method developed here enables one to decrease considerably in the static component of the force of penetration of bodies to ground. The results obtained can be used to design technical devices for relevant technologies and to choose operating regimes for these devices.

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