Experimental results of [1] and new experimental data obtained on an apparatus analogous to that in [1] are shown in Fig. 1. The experimental results lie close to the curve corresponding to Eq. (2). The coincidence is completely satisfactory, since the animal fluidization rate cannot be determined without an error due to the presence of the transitional region on the experimental curve of bed resistance vs gas velocity [2].

The new law in fluidized-bed hydrodynamics derived from the experimental results — that the kinetic component of the energy-flux density of the fluidizing gas at which fluidization of the material begins is independent of the gas pressure above the bed — has a clear practice physical meaning and may be used not only for practical purposes but also in the theory of fluidization.

NOTATION

ρ, p, w, current density, pressure, and minimum fluidization velocity of the gas; ρ_0, p_0, w_0, density, pressure and minimum fluidization velocity of gas in the conditions of a single experiment; A, constant for the given material.

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DYNAMIC PROPERTIES OF A LOOSE GRANULAR BED

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UDC 532.546

A dynamic model of a loose granular medium is developed, and with its help the process of sudden arrest of the bed is studied. The model is compared with experiment.

In industrial processing loose media usually pass through a stage characterized by loose packing of the particles. Because of the low mechanical stability of loose systems dynamic elasticity, similar to elasticity in a concentrated dispersed medium, can arise in them [1].

An example of the manifestation of dynamic elasticity is the effect of sudden arrest, similar to hydraulic shock in a liquid, of a loose bed when, owing to an increase in the pressure on the barrier for a short time, damped oscillations of the granular mass develop in the bed, whose frequency corresponds to the resonance frequency of the vibrating bed [1]. The spontaneous appearance of this situation, for example, accompanying the collapse of loose material in a vertical channel, mine, pneumatic transport and release or bulk materials from containers can be accompanied by collapse of the protective surfaces, dust formation, etc. [2]. Deliberate excitation of free oscillation facilitates the removal of "obstructions" and sticking in pneumatic transport [3]. It can also be employed to determine the dynamic characteristics of a loose granular bed by the impact method.

These phenomena always appear when conditions are formed in the system under which dynamic elastic forces predominate over dissipative forces. It is easy to formulate them starting from the general relations of the hydromechanics of heterogeneous systems. These include the existence of the initial loose packing, dynamic "impassibility" of the bed and impact loads exceeding the mass forces in the system. Taking into account the region of extension and application of the phenomena, we shall study the behavior of the system in a gravitational field.

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An excess $\Delta\varepsilon$ of the porosity ε prior to impact over the porosity of a dense layer ε_{cr} should lead to dynamic $\delta\varepsilon$ compressive deformation*

$$\Delta\varepsilon = \varepsilon - \varepsilon_{cr} \approx \delta\varepsilon \geqslant \Delta\varepsilon_{min}. \tag{1}$$

The magnitude of the minimum dynamic deformation $\Delta\varepsilon$ is determined from the condition that the pulsations of the pressure equal the dry friction forces. Using the equation of state of an isothermal ideal gas in the differential form (4), we can derive a formula for evaluating the minimum preimpact looseness:

$$\frac{\Delta\varepsilon_{min}}{\varepsilon_{cr}} \approx \frac{2}{\pi}\alpha(1-\varepsilon_{cr})\frac{G}{P_0}. \tag{2}$$

Formula (2) shows that the condition (1) is very "soft" and is satisfied comparatively easily. Thus for corundum particles with $H_b = 0.1$ m, $\Delta\varepsilon_{min} \simeq \varepsilon_{cr} 10^{-3}$.

The condition of dynamic "impassability", necessary for maintaining high elastic forces in the bed during the entire vibrational process, is determined from the expression

$$\tau_r/(nT_0) \gg 1, \tag{3}$$

where τ_r is the relaxation time of the gas pressure in the granular bed, determined by the linear filtering of excess gas from the pores. Given n and T_0, with the help of (3) it is not difficult to evaluate the limiting values of the parameters (d_{pmax}, ε_{max}, H_{min}), under which the elastic forces in the fill will relax more slowly than the oscillations maintained by them decay.

The condition (3) is n times ($\sim$ by an order of magnitude) "harder" than the condition for the development of forced elastic oscillations in a vibrating fluidized bed ($\omega_0\tau_r > 1$). Therefore the sharpest development of free oscillations should be expected in beds consisting of approximately $\sqrt{n}$ times smaller particles than beds which are in a state of intensive vibrational fluidization. Such beds always contain some submicron- and micron-size particles, which impart thixotropic properties to coarsely dispersed systems [4]. Thus together with pseudothixotropy, consisting of "linearization" of the friction in the bed owing to a reduction of the relative fraction of dry friction forces in the force balance of the system and sometimes called vibrothixotropy [5], in the development of free oscillations in the limit complete temporary vanishing of dry friction forces and a transition of the system into a truly liquid state, as sometimes happens during the vibration of soil [6], can be expected. The third condition is sufficient. To find it it is necessary to solve the problems of the dynamics of a loose granular bed.

Basing our analysis on experience in applying softly plastic models to describe the dynamics of dense granular media in plastic flow and vibrational loading processes [5, 7], we shall regard the system as a quasihomogeneous medium, characterized by viscoelastoplastic properties, deformations in which develop when limiting equilibrium breaks down in the framework of the loose bulk medium and give rise to compression of the dynamically "fixed" ideal gas (Fig. 1). For all its outward triviality the model is distinguished profitably from similar models [6-8] by the fact that the quantities appearing in it are physically well defined, which makes it possible to carry out analytical calculations practically without invoking empirical data.

The total hydromechanical pressure P on a barrier in such a system consists of three components: the elastic P'_g, viscous P''_g, and plastic P_p. The components P'_g and P''_g belong to the same substratum — to the gas — and are physically inseparable, and their sum corresponds to the hydrodynamic gas pressure P_g in the gaps between the particles: $P'_g + P''_g = P_g$. The plastic component, however, corresponds to shear stresses in the layer and can be determined from the mechanical pressure of the particles on a control surface.† Thus $P = P_g + P_p$. Obviously, this simple relation can be written down only under conditions ensuring

*Since most of the deformation of a loose bed is determined by gaseous gaps, the particles may be assumed to be absolutely rigid.
†The technique of the experiment on determining the components of the force balance for vibrating fluidized beds is developed in [9].

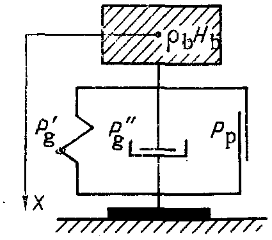

Fig. 1. Dynamic model of a loose granular bed.

dynamic "impassability" of the bed mentioned above and in the absence of turbulent transport. It also determines the character of the mechanical deformations of the bed — structural deformations. This model ignores the collisional elastoplastic interaction of the rigid framework of the bed with the boddom, characteristic of compact and "semicompact" mobile beds.

We shall find the magnitude of the elastic pressure on the barrier from the linearized equation of state of an isothermal gas:

$$P_g'(H_b, t) = \frac{\pi^2}{4}\frac{P_0}{\varepsilon_b H_b}X(t) = \frac{\partial E_p}{\partial X}. \tag{4}$$

Here and below we employ the idea that free oscillations in the granular bed occur in a form close to a standing wave of the first (quarter-wave) mode with maximum deformations at the barrier and zero deformations at the top boundary. Therefore the average deformation of the compression of the framework of the layer $X(t) = \frac{2}{\pi}x(h, t)$.

Viscous losses in the model are determined by the nonuniformity of the velocity profiles of the gas and solid particles in the absence of any appreciable filtrational slipping of the phases and are analogous to the "normal" volume viscosity. Their magnitude depends on the velocity relaxation time of the phases τ_v and the rate of deformation of the framework:

$$P_g''(H_b, t) = \frac{\pi^2}{4}\frac{P_0}{\varepsilon_0 H_b}\tau_v\dot{X}(t) = \frac{\partial E_p'}{\partial X}. \tag{5}$$

Plastic losses for coarsely dispersed systems ($d_p \geqslant$ 1–10 μm) will be of the order of fractions of the weight of the column of material and, taking into account the direction of motion, are given by

$$P_p(t) = P_f = \alpha\rho_b g H_b \operatorname{sign}(\dot{X}), \tag{6}$$

where $\alpha \leqslant 0.5$ is the reduced coefficient of friction, which takes into account the conditions for formation and the mechanical properties of the starting moving bed and also limits the effect of the walls of the vessel. It turns out that because of the looseness of the starting packing and the short-time nature of the lateral displacement of the particles in the vibrational cycle the plastic component can be approximated by the "soft" force characteristic under conditions that the displacements of the layer in the transverse direction are limited. Taking into account the small contribution of the dry friction force to the formation of the developed free oscillations and the difficulty of determining it a priori, we shall assume that the reduced coefficient of friction α is a free empirical parameter.

We write down the Lagrangian equation for the system

$$\frac{d}{dt}\left(\frac{\partial E_k}{\partial \dot{X}}\right) = -\frac{\partial E_p}{\partial X} - \frac{\partial E_p'}{\partial X} - P_p \tag{7}$$

where the kinetic energy of the bed is defined by the relation $E_k = \frac{1}{2}m\dot{X}^2$. We finally obtain the equation sought, in which the coefficients are assumed to be constant:

$$\ddot{X} + \omega_0^2\tau_v\dot{X} + \alpha g \operatorname{sign}(\dot{X}) + \omega_0^2 X = 0, \tag{8}$$

where $\omega_0 = \frac{\pi}{2} \frac{a}{H_b}$, $a = \sqrt{P_0/(\varepsilon_0 \rho_b)}$.

The solution of Eq. (8) with the initial conditions*

$$X(0) = 0, \quad \dot{X}(0) = V_0 \tag{9}$$

has the form

$$\begin{gathered} X = \mp \Delta_f + \Delta_i \psi \exp(-\delta f_0 t) \sin(\omega_b t + \varphi_x), \quad \dot{X} \gtrless 0, \\ P = P_i \psi \exp(-\delta f_0 t) \sin(\omega_b t + \varphi_r), \end{gathered} \tag{10}$$

where

$$\Delta_f = \frac{\alpha g}{\omega_0^2}; \quad \Delta_i = \frac{V_0}{\omega_0}; \quad P_i = \frac{\pi}{2} \rho_b a V_0; \quad \omega_b = \beta\omega_0;$$

$$\beta = \sqrt{1 - \left(\frac{\delta_0}{2\pi}\right)^2}; \quad \delta_0 = \pi\omega_0\tau_v; \quad \delta = \delta_0/\beta; \quad \gamma = 1 - \frac{\delta_0^2}{2\pi^2};$$

$$\psi = \frac{1}{\beta} \sqrt{1 \pm \frac{\Delta_f}{\Delta_i}\omega_0\tau_v + \left(\frac{\Delta_f}{\Delta_i}\right)^2}, \quad \dot{X} \gtrless 0;$$

$$\varphi_x = \operatorname{arctg}\left(\beta \frac{\pm \Delta_f}{\Delta_i \pm \Delta_f \frac{\omega_0\tau_v}{2}}\right), \quad \dot{X} \gtrless 0;$$

$$\varphi_p = \operatorname{arctg}\left(\beta \frac{\pm \Delta_f + \Delta_i\omega_0\tau_v}{\Delta_i\gamma \mp \Delta_f \frac{\omega_0\tau_v}{2}}\right), \quad \dot{X} \gtrless 0.$$

The properties of the solution (10) depend on the ratio of the forces, which is determined by the impact velocity V_0 (Fig. 2). For low velocity, when the inertial forces do not exceed the dry friction forces, there are no structural deformations. The critical impact velocity, ensuring that structural deformations will appear, is found from the condition $X = \Delta_f$ in the form $V_{cr} = \sqrt{3} V_f = \sqrt{3} \Delta_f \omega_0$.

If the near-critical velocities $V_0 \gg V_{cr}$, when the deformations are still small and the moduli of the elastic forces do not exceed the dry friction forces, are used, then the motion will be of a nonoscillatory character, representing the standard compaction accompanying shaking.† At the same time the gas compressed in the gaps between the particles will slowly filter out of the bed, and will not have any effect on the dynamics of the bed.

As the impact velocity increases the degree of compression of the bed and its rate of compaction will increase. However as soon as the elastic forces equal the dry friction forces, after the compression phase elastic restoration – expansion – of the volume of the bed will begin, which explains the well-known difficulties of impact compaction of dusty materials compared with coarse-grained materials. The minimum impact velocity, giving rise to post impact restoration, is found from the condition $X = 2\Delta_f$ and equals $V_2 = \sqrt{8}\, V_f$. Further, for $V_0 = (\sqrt{8} - \sqrt{24}) V_f$ the process remains aperiodic, since the magnitude of the elastic expansion of the bed after impact compaction does not exceed the initial level. This process, and also the vibrational motion following it when $V_0 > V_3 = \sqrt{24} V_f$ (more precisely, its first two phases), are described by the dependences

$$\begin{gathered} \frac{X}{\Delta_f} = \mp 1 + \sqrt{\bar{V}^2 + 1} \sin(\omega_0 t + \varphi_x), \quad \dot{X} \gtrless 0; \\ \bar{V} = \frac{V_0}{V_f}; \quad \varphi_x = \operatorname{arctg}(\pm 1/\bar{V}), \quad \dot{X} \gtrless 0. \end{gathered} \tag{11}$$

*In practice different methods for giving the initial perturbation can be encountered, for example, pneumatic [3, 10], which under certain conditions can be put into the form (9).
†The bulk loads on a conveyor belt, in a grain silo, etc. are apparently in a close dynamic state [2].

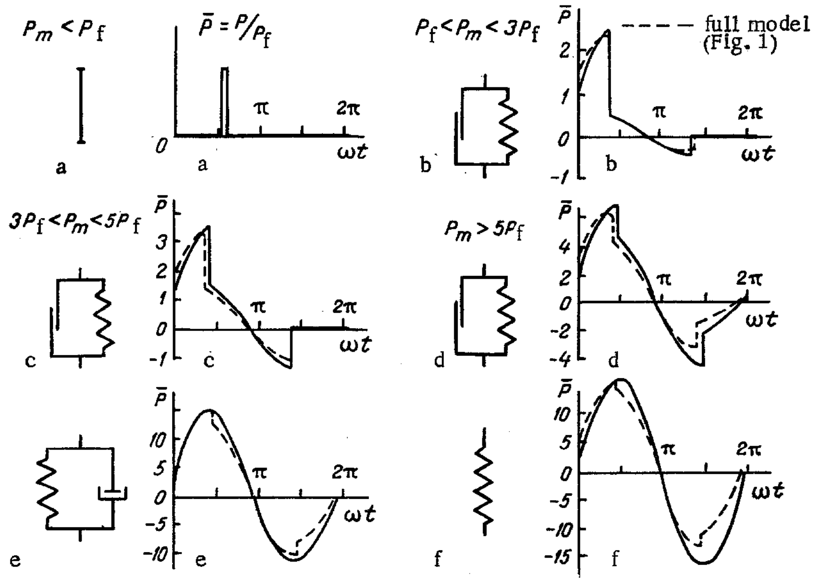

Fig. 2. Dynamic regimes of a loose granular bed: a) immobile, $\bar V^2$ = 0-3; b) impact regime without restoration; $\bar V^2$ = 3-8; c) impact with imcomplete restoration (aperiodic motion), $\bar V^2$ = 8-24; d) elastoplastic, $\bar V^2 > 24$; e) viscoelastic, $\bar V^2 = 225$, $\delta > 0.25$; f) elastic, $\bar V^2 = 225$, $\delta < 0.25$.

The damping of such oscillations owing exclusively to dry friction, as is well known, is linear, and their period remains unchanged. Therefore the amplitude of the i-th oscillation is given by

$$X_i = X_1 - \frac{i-1}{\pi\sqrt{3}} V_{cr} T_0. \qquad (12)$$

The next to last (viscoelastic) regime of the vibrational motion of the bed, dictated by the model, will appear at impact velocities which ensure that the action of viscous friction will predominate over the dry friction: $V_0 > V_4 = \Delta_f/\tau_v = \frac{\pi}{\sqrt{3}\,\delta_0} V_{cr}$. The quantity V_4 for small particles ($d_p < 0.1$ mm) approximately equals $10V_{cr}$. Therefore for $\bar V > 10\sqrt{3}$ it should be expected that the system will become linear.

$$X = \Delta_i \frac{1}{\beta} \exp(-\delta f_0 t) \sin(\omega_b t). \qquad (13)$$

The pressure as a function of time in elastoplastic regimes during the first two phases is described by the dependence

$$P = P_i \sqrt{1 + 1/\bar V^2} \sin(\omega_0 t + \varphi_p), \quad \varphi_p = \mathrm{arctg}(\pm 1/\bar V), \quad \dot X \gtrless 0, \qquad (14)$$

which includes the jump in the pressure $\delta P_1 = P_f = \alpha \rho_b g H_b$ at the moment of the impact (t = 0) and $\delta P_2 = -2P_f$ at the moment of the transition from the compression phase to the expansion phase $t_m = (\pi/2 - \varphi_p)/\omega_0$. The total duration of the impact process, characterized by the presence of compressive forces in the bed, equals $t_i = (\pi - \varphi_p)/\omega_0$.

The maximum pressure on impact

$$P_m = P_i \sqrt{1 + 1/\bar V^2} \approx P_i. \qquad (15)$$

The last approximate relation makes it possible to carry out calculations for $\bar V \approx 10\sqrt{3}$, without determining the reduced coefficient of dry friction α. As one can see, Eq. (15) is identical, to within a factor of π/2, to the well-known formula of Zhukovskii for a hydraulic shock in a liquid. It is characteristic that in the expansion phase in elastoplastic regimes (Figs. 2c and d) the pressure of the gas phase is greater than the total pressure by the amount of the dry friction forces. According to [11] the well-known peak in the pressure in a granular bed under conditions of pseudofluidization is of an analogous nature.

It is convenient to represent the law of decay of the pulsations of the gas pressure in the elastoplastic regime in "segments"

$$\frac{\Delta P_i}{\Delta t_i} = \frac{2}{\pi} \rho_b a V_{cr} \omega_0, \tag{16}$$

where ΔP_i is the pressure drop between two arbitrary oscillations and Δt_i is the time between them. From here we obtain a formula for determining experimentally the reduced coefficient of friction

$$\alpha = \frac{\pi}{2\sqrt{3}} \frac{1}{\rho_b g a} \frac{\Delta P_i}{\Delta t_i}. \tag{17}$$

For the conditions of the viscoelastic state

$$P = P_i \frac{1}{\beta} \exp(-\delta f_0 t) \sin(\omega_b t + \varphi_p); \quad \varphi_p = \operatorname{arctg}\left(\frac{\beta\delta_0}{\gamma\pi}\right);$$
$$P_m = P_i \frac{1}{\beta} \exp(-\delta f_0 t) \approx P_i. \tag{18}$$

Analyzing the effect of the value of the logarithmic damping decrement δ on the dependences obtained, we find that when the amplitude of the deformations Δ_i decreases monotonically as δ increases the maximum pressure exerted by the bed on the barrier will at first decrease also (to the value $\delta \simeq 2$), occurring for $\delta < 0.25$ to within 10% at the time $t = T_0/4$, while the frequency of the oscillations ω_b for $\delta \leq 2$ to within 5% equals the characteristic frequency of the elastic oscillations ω_0. The final approximate expressions in (18) were written down for this case. As δ increases further $\delta > 2$ (which can be realized, for example, by using low beds, large particles, or extremely loose packing) and the viscous friction forces increase the dynamic rigidity of the system begins to increase and will bring about an increase in the pressure of the bed on the bottom, which for $\delta > 3$ will be greater than the elastic component of the pressure P'_g. This increase will bring about a restructuring of the nature of the pressure variations as a function of time from practically harmonic (for $\delta < 0.25$) to triangular with an instantaneous rise up to the maximum for $\delta > 3$ (for equal areas under the curves). However, since the energy dissipated in a half-period equals 100% of the kinetic energy of the impact already for $\delta = 1$,* free oscillations under these conditions are impossible and the state within $\delta > 1$ is of no practical value.

The results of the computational and experimental determination of the total pressure on the barrier for different impact velocities are shown in Fig. 3. The different character of the damping of the vibrational process, exponential at the beginning and linear at the end (Fig. 3b), indicates systematic domination of the viscous and plastic components, respectively. On the whole, however, analysis of the results presented leads to the conclusion, without going into details, that the dynamic behavior of the model describes adequately the dynamic behavior of a loose granular bed.

NOTATION

a, velocity of sound in an equilibrium dispersed medium; d_p, diameter of the particles, E_p and E_k, potential and kinetic energy; f_0, characteristic frequency; g, acceleration of gravity; $G = \rho_b g H_b$; H, total depth of the bed; h, instantaneous depth of the bed; n, number of free oscillations before decay; P, pressure; $T_0 = 1/f_0$, period of characteristic elastic oscillations; t, time; V, impact velocity; $\bar{V}$, dimensionless velocity; X, volume-averaged linear deformation of the bed; x, linear deformation of an element; α, reduced coefficient of internal dry friction; δ, logarithmic damping decrement; ε, porosity; μ, dynamic viscosity; ω, angular frequency; ρ, density; $\tau_r = 150\frac{1-\varepsilon_0}{\varepsilon_0^3}\frac{\mu g}{P_0\rho_p}\left(\frac{H_b}{d_p}\right)^2$ and $\tau_v = H_b^2/(P_0\tau_r)$, relaxation times of the pressure and velocity; φ, initial phase. Indices: i, order number of the oscillation; m, maximum; g, gas; cr, critical; 0, initial parameters prior to impact; p, pressure; b, layer; f, friction; i, impact; x, displacement; and, p, particles.

*Determined from the well-known relationship $\delta = NT_0/(2E_c)$, which reveals the energy significance of δ, where N is the dissipated power averaged over a period.

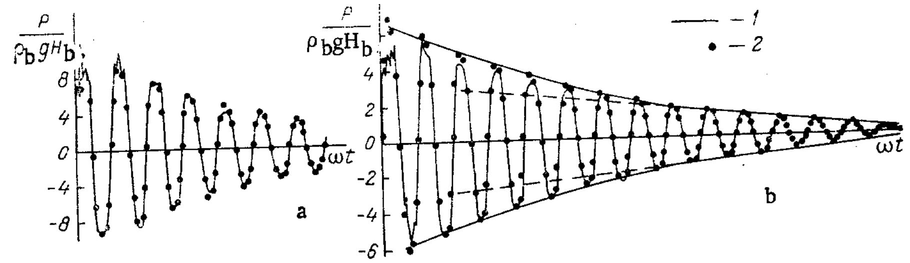

Fig. 3. Change in the total pressure of the layer on the barrier in time (1 — experiment; 2 — calculation using (10): a) ash (H_b = 0.165 m; V_0 = 0.767 m/sec; d_p = 23 μm); b) cinders of mercury—antimony concentrate (H_b = 0.92 m; V_0 = 0.313 m/sec; d_p = 10 μm).

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ELECTROCHEMICAL PROPERTIES OF COMPOSITE MATERIALS BASED ON GRAPHITE AND VANADIUM DISILICIDE

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UDC 541.13

Electrodes with different composition were prepared by the method of pressing followed by sintering of the graphite and vanadium disilicide powders, and their electrochemical and corrosion properties in water solutions of electrolytes were studied.

Vanadium disilicide, as demonstrated in [1, 2], exhibits high corrosion resistance in water solutions of mineral acids owing to the formation of silicon oxide (SiO_2), which is insoluble in these electrolytes on its surface.

The high corrosion resistance of VSi_2 and its high electrical conductivity [3] suggest that this compound can be employed as an electrode material in carrying out cathodic and anodic electrochemical processes in water solutions of electrolytes.

It should be noted, however, that according to [4] a passive oxide film, exhibiting semiconductor properties with a large gap width, is formed on silicon with anodic polarization in water solutions of electrolytes. Because of the low conductivity of this film

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