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THE RESEARCH ON RAPID GRAVITY FLOWS OF PARTICULATE SOLIDS

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Key words and phrases: concentration profiles; rapid gravity flow; X-ray method.

Abstract: An experimental method of the uncontact investigation of concentration profiles during rapid gravity flow of particulate solids is suggested. The method supposes the simultaneous X-ray examination of both particulate solids distribution in the flow and control samples, having certain concentrations of particles, by means of the use of the common X-ray radiogram. The method developed was used to investigate the concentration profiles in the course of rapid gravity flows of spherical ceramic particles on a rough chute. The accuracy of the earlier developed experimental and analytical method supposing the formal analogy between the granular medium under rapid shear and dense gas is checked up by the X-ray method.

Nomenclature

d – diameter of particles, m;
du/dy – shear rate, s^{-1};
g – gravity acceleration, $m \cdot s^{-2}$;
$G(x_1)$ – material distribution function along a horizontal coordinate x_1 (Fig. 1), $kg \cdot m^{-2} \cdot s^{-1}$;
h – bed depth, m;
$P(y)$ – analogue of hydrostatic pressure, $N \cdot m^{-2}$;
$u(y)$ – flow velocity, $m \cdot s^{-1}$;
y, x_1 – Cartesian coordinates (Fig. 1).

Greek letters

α – chute inclination angle, deg.;
α_0 – the angle of repose of the material, deg.;
ε – fraction of void volume, $m^3 \cdot m^{-3}$;
$\overline{\varepsilon}$ – bed dilatation, $m^3 \cdot m^{-3}$;
ε_0 – fraction of the void volume of dense packed particles, $m^3 \cdot m^{-3}$;
χ – coefficient of the granular medium state equation (3).

Introduction

The rapid gravity flows of particulate solids is a widespread type of rapid shear flows taking place in the course of many natural phenomena and technological operations. However at present the adequate forecasting the flow parameters faces a lot of experimental and analytical problems. Rapid shear flow investigation is a field of granular media mechanics. Such flows is often called grain-inertia flow as, internally, momentum is carried by the inertia of the particles and exchanged during interparticle collisions.

Adapting of a Goodman-Cowin's model [1] of a rapid shear flows of granular materials, based on the main statements of the continuous medium mechanics, Savage [2] developed the model for particles rapid gravity flow down an incline. Later, taking into acount the evident drawbacks of the continuous medium models, Ogawa et.al. [3], Jenkins and Savage [4], Ackermann and Shen [5] and Savage [6] developed a model of a rapid gravity flow based on the microstructural approach. These authors determined the stress tensor by analyzing momentum translation during particle collision and solving the system of equations on the conservation of momentum and fluctuation energy.

But the assumptions made by the authors led to errors in the description of flows. Particularly, these errors being quite apparent in numerical modeling of granular particles flow down a steep incline carried out by Hutter and Sheiwiller [7]. Moreover, it was found out [7] that models require an exact statement of boundary conditions which are difficult to determine.

Ackermann and Shean [5] used geometrical analysis of the shear flow microstructure and came to the conclusion that the gravity flow should be characterized by a considerable lateral mass transfer (quasi-diffusion) which must be taken into consideration for an adequate flow modelling. However, it seems that the authors [5] restrict the possibilities of the approach when they proceed from the assumption made that the collision conditions do not depend on the solid phase concentration. The analogous assumption is used also in the most analytical investigations of rapid shear flows.

Campbell and Brennen [8] carried out a direct computer modeling of a rapid shear flow of cohesionless nonelastic rough particles. One of the most important results of their computational experiment is the conclusion that the effective coefficient of friction determined as a shear stress to normal stress ratio depends on the solid phase concentration. Similar results were obtained experimentally by Savage [6].

A close consideration of all the above mentioned papers permits the conclusion that the assumptions made by the authors about the absence of momentum transfer due to particles quasi-diffusional displacement and the assumption that the effective coefficient of friction does not depend on concentration are very approximate. As a consequence the corresponding models predict the existence of a steady gravity flow only within a narrow range of bed inclination angle values, and allow the description of velocity profiles and solid particles distribution in full, especially in thin layers and the flow boundary areas.

For all the reasons cited above and tacking into account the problems connected with the models require an exact statement of boundary conditions it seems impossible to use the existing models for an adequate predicting of functions $u(y)$ and $\varepsilon(y)$.

Considerable experimental difficulties complicate the rapid gravity flow modeling of granular materials. It is rightly pointed out in [6] that rapid gravity flows of particles down a steep incline appear to be extremely complicated for an experimental study despite their apparent simplicity. The analysis of the results of such investigations of flows shows [6, 7] that the main difficulties arise from the high sensitivity of gravity flows to an internal probe and the largest boundary effects impeding in the use of visual investigation methods At present these difficulties promote the appearance of new alternative experimental methods, for example [9].

In the present paper an experimental method of the uncontact investigation of concentration profiles during rapid gravity flow of particulate solids is suggested. According to this method a solid phase concentration is determined by means of the X-ray photography. The X-ray method is used to check the adequacy of the earlier developed [10] experimental and analytical method of determination of the velocity and concentration profiles in the rapid gravity flows of particulate solids on a rough chute.

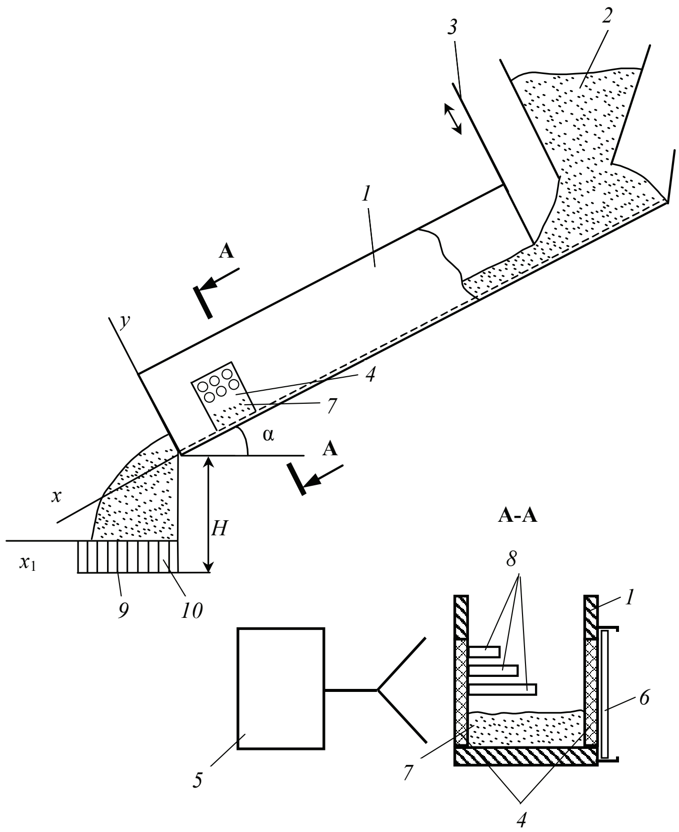

Fig. 1 Schematic of the experimental unit:
1 – channel; *2* – dosage device; *3* – gate; *4* – gaps closed by organic glass;
5 – X-ray source; *6* – cassette containing the X-ray film; *7* – gravity flow of particles;
8 – control samples; *9* – tray; *10* – cells

The experimental part of the method [10] consists in sending a granular material down a stationary incline and collecting the particles in a tray containing a number of cells (Fig. 1).

In accordance with the method developed, the experimental data include the bed depth h at the discharge threshold in a steady flow, time t, the material distribution function $G(x_1)$ along a certain horizontal coordinate axis x_1 located at a vertical distance H from the discharge threshold and the bed inclination angle α (Fig. 1).

The equations connecting the profiles of velocity $u(y)$ and the fraction of void volume $\varepsilon(y)$ in the rapid gravity flows of particulate solids on a rough chute are formulated [10] as follows

$$|\vec{u}| = \frac{x_1 - y\sin\alpha}{\cos\alpha\sqrt{(H + y\cos\alpha - (x_1 - y\sin\alpha)\,\mathrm{tg}\alpha)\dfrac{2}{g}}}; \qquad (1)$$

$$u(y, x_1)\rho\big(1 - \varepsilon(y)\big) = G(x_1)\,. \qquad (2)$$

Using the hypothesis [10] about the analogy between the parameters of the granular medium under the rapid shear and the corresponding parameters of the dense gas we obtained [11] the following equation of the granular medium state

$$P(y)\bar{\varepsilon}(y) = \chi\left(\frac{du}{dy}\right)^2, \qquad (3)$$

where $P(y) = \int\limits_{h-y}^{h} \rho^*(y) g \cos\alpha dy$ is the hydrostatic pressure analogue; $\bar{\varepsilon}(y) = \frac{\varepsilon(y) - \varepsilon_0}{1 - \varepsilon(y)}$ is the bed dilatation, du/dy is the shear rate, χ is the equation coefficient of the granular medium state.

The equations (1) – (3) make up a closed system, relative to the functions $u(y)$, $y(x_1)$, $\varepsilon(y)$ and $P(y)$. The profile of velocity and fraction of void volume are obtained solving the system of these equations by using the successive approximations.

The method allows to predict the complex concentration profiles taking place in the rapid gravity flows having low bed heights. The method adequacy was indirectly corroborated in the course of repeated segregation dynamics modeling [10]. In present paper the direct corroboration of this method is obtained by means of the X-ray photography.

Experimental method and unit

In order to eliminate the drawbacks of the traditional visual and probe methods an experimental method of the uncontact determination of concentration profiles during rapid gravity flow of particulate solids is used by means of the X-ray photography.

The experimental unit shown schematically in Fig. 1 is analogous in its basis to the one used earlier in the course of realization of the experimental and analytical method [10], described in the previous paper section. The unit consists of an inclined chute of square cross-section having a rough bottom. The chute slope could be adjusted. To control the depth and length of the moving bed a gate was installed at the chute entrance. At a distance from the discharge threshold of the chute there was a horizontal tray used to collect the particles falling down the chute. To determine the distribution of particles along the bed depth the tray contained cells.

In order to provide the possibility of the direct determination of the concentration profiles the side walls of the chute had two gaps located opposite each other near the discharge threshold. The wall gaps were closed by plates making up from an organic glass. This material, being very pervious for the X-ray, was used also for the making up the rough bottom in the bottom area between the gaps. Outside the channel at its opposite wall gaps a X-ray source and cassette with the radiograph film are installed. The X-ray photography is carried out during the steady states of gravity flows. In order to increase its accuracy the method supposes the simultaneous X-ray examination of both particulate solids distribution in the flow and control samples, having certain concentrations of particles, by means of the use of a common X-ray film. The control samples were fixed on the organic glass into the channel. This approach allows to eliminate the random mistakes arising in the consequence of the dissimilarity of the radiograph films and their different development conditions. As a result a correct correlation function between the solid phase concentration and the light permeability of the radiogram is obtained.

The consecution of the method realization is presented in Fig. 2 as an algorithm scheme.

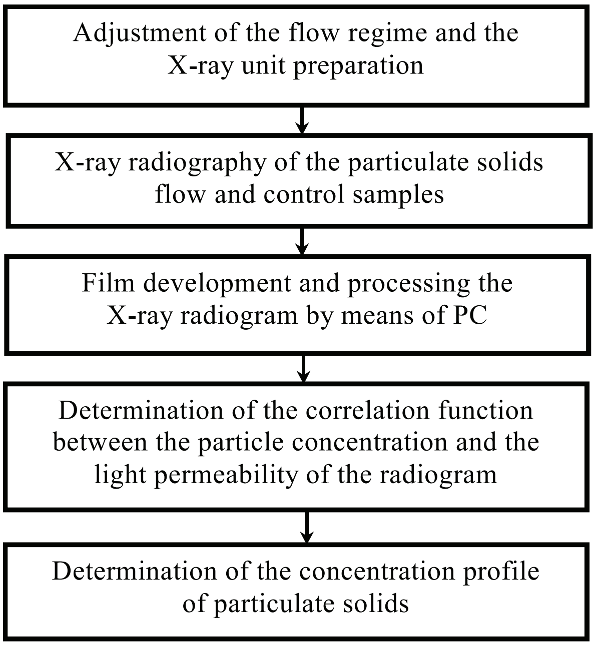

Fig. 2 Algorithm scheme of the X-ray method of the concentration profile determination

Investigation results and their discussion

The method developed was used to investigate the concentration profiles in the course of rapid gravity flows of spherical ceramic particles on a rough chute.

The particle diameter was equal to $6.6 \cdot 10^{-3}$ m. The investigation was carried out under conditions similar to steady rapid gravity flow. These conditions were established by fixing the incline (its roughness being half the particle diameter) at an angle to the horizon equal to the angle of repose of the material approximately. The desired roughness of the incline was achieved by fixing a perforated plate above the smooth base at a distance of half the particle diameter. The dimension of the holes in the plate was equal to 2- to 3-times the particle diameter and the free cross-sectional area was 70 % of plate area.

During the experimental determination of velocity profiles at the threshold of discharge at various lengths of sending bed, it was established that the flow becomes steady at 0.35 m. Velocity profiles at a bed length of 0.35 and 0.6 m differ less than 5 %. The particle bed depth at the threshold of discharge was estimated by the method suggested in [11].

The steady sliding flows having a small bed depth being equal to 5 – 10 times the particle diameter were tested in the research. These flows are very interest for the study due to the complex structure of their failure zones causing original interaction effects of particles.

For example Fig. 3 shows the X-ray radiogram of a rapid gravity flow of spherical ceramic particles on the rough chute at 0.6 m incline length.

The corresponding profiles of velocity and the fraction of void volume in this flow are shown in Fig. 4.

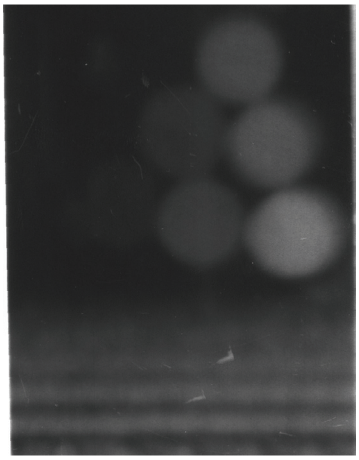

Fig. 3 X-ray photograph of the control samples (at the top of the radiogram) and spherical ceramic particles undergoing rapid gravity flow on a rough chute

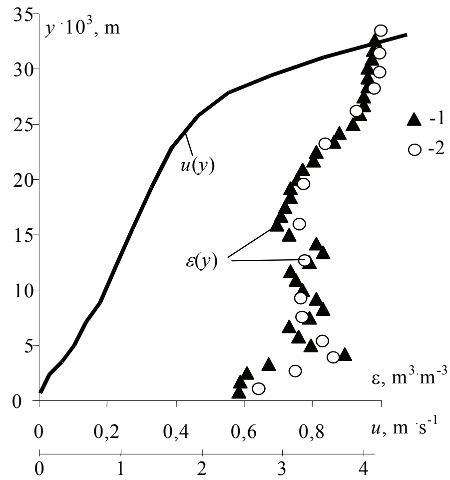

Fig. 4 Profiles of velocity *u*(*y*) and the fraction of void volume ε(*y*) during ceramic particle gravity flow down a rough chute: 1 obtained by the X-ray method; 2 obtained by the experimental and analytical method [10]

Thereby, it should be pointed out that the profile of the fraction of void volume, being reverse to the solid concentration profile, was obtained in accordance with the two different methods, i.e. by means of the earlier presented [10] experimental and analytical method and X-ray photography.

The results shown in Figs. 3 and 4 allow to observe the following two original features of the particle behaviour were found out in such flows. The first one consists in the formation of more compact layer areas in the central part of the bed. On the other hand the peripheral flow areas located at the free surface and the bottom of the bed are characterized by the highest values of the fraction of void volume.

The second feature of the flow consists in the tendency of particles to organize regular columns especially under low values of the fraction of void volume in the central part of the bed.

The X-ray method is used to check the accuracy of the earlier developed [10] experimental and analytical method supposing the formal analogy between the granular medium under rapid shear and dense gas and taking into consideration the experimental distribution function of particles during their free-fall stage after the discharge threshold of the chute. The comparison of the results obtained by means of these two investigation methods shown in Fig. 4 testifies to the fact of their satisfactory adequacy. Besides, it is noteworthy, that the results of the X-ray photography may be regarded as a direct demonstration of the correctness of the method forecasting the rapid shear flow parameters [10] on the basis of a formal analogy between the particulate medium under going rapid shear and dense gas.

Conclusion

At present the adequate analytical description of rapid gravity flows of particulate solids seems to be very difficult in consequence of the problems concerning an exact statement of boundary conditions and the shear stress determination especially in the case of the flows having small bed depths. The experimental investigations also face a lot of problems which are closely connected with the high sensitivity of gravity flows to an internal probe.

In the present paper an experimental method of the uncontact investigation of concentration profiles during rapid gravity flow of particulate solids was suggested. According to this method a solid phase concentration is determined by means of the X-ray photography. In order to increase its accuracy the method supposes the simultaneous X-ray examination of both particulate solids distribution in the flow and control samples, having certain concentrations of particles, by means of the use of the common X-ray radiogram. This approach allows to obtain a correct correlation function between the solid phase concentration and the light permeability of the radiogram.

The method developed was used to investigate the concentration profiles in the course of rapid gravity flows of spherical ceramic particles on a rough chute. The steady sliding flows having a small bed depth (5 – 10 particle diameters) were tested in the research. The following two original features of the particle behaviour were found out in such flows. The first one consists in the formation of more compact layer areas in the central part of the bed. On the other hand the peripheral flow areas located at the free surface and the bottom of the bed are characterized by the highest values of the fraction of void volume. The second feature of the flow consists in the tendency of particles to organize regular columns especially at low values of the fraction of void volume.

Besides the X-ray method was used to check the accuracy of the earlier developed [10] experimental and analytical method supposing the formal analogy between the granular medium under rapid shear and dense gas and taking into consideration the experimental distribution function of particles during their free-fall stage after the discharge threshold of the chute. The comparison of the results obtained by means of these two investigation methods testify to the fact of their satisfactory adequacy. It is noteworthy, that the results of the X-ray photography may be regarded as a direct demonstration of the correctness of the method forecasting the rapid shear flow parameters [10] on the basis of a formal analogy between the particulate medium under going rapid shear and dense gas.

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Исследование быстрых гравитационных потоков зернистых материалов

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Ключевые слова и фразы: быстрый гравитационный поток; метод рентгенопросвечивания; концентрационные профили.

Аннотация: Разработан метод бесконтактного исследования концентрационных профилей в быстром гравитационном потоке зернистого материала. Метод предполагает одновременное рентгенопросвечивание распределения в потоке и контрольных образцов, имеющих фиксированную концентрацию, и получение общей рентгенограммы. Разработанный метод использован для исследования концентрационных профилей при движении быстрых гравитационных потоков сферических керамических частиц на шероховатом скате. С помощью рентгенографического метода проведена проверка адекватности ранее разработанного экспериментально-аналитического метода, устанавливающего формальную аналогию между зернистой средой при быстром сдвиге и плотным газом.

Untersuchung von schnellen Gravitationsströmen der körnigen Stoffe

Zusammenfassung: Es ist die Methode der kontaktlosen Untersuchung der Konzentrationsprofile im schnellen Gravitationsstrom des körnigen Stoffes erarbeitet. Die Methode setzt das gleichzeitige Röntgendurchleuchtung der Partikelnverteilung im Strom und der die fixierte Konzetration gehabten Kontrollmuster, und die Erhaltung des gesamten Röntgenbildes voraus. Die erarbeitete Methode ist für die Untersuchung der Konzetrationsprofile bei der Bewegung der schnellen Gravitationsströme von sphärischen keramischen Partikeln auf dem unebenen Abhang benutzt. Mit Hilfe der röntgengraphischen Methode ist die Prüfung der Adäquatheit der früher erarbeiteten experimentell-analytischen Methode durchgeführt. Diese Methode setzt die Formalähnlichkeit zwischen dem körnigen Medium bei der schnellen Verschiebung und dem Dichtgas fest.

Recherche des flux rapides de gravitation des matétiaux granulés

Résumé: Est élaborée la méthode de l'étude sans contact des profils de concentration dans un flux rapide de gravitation des matétiaux granulés. La méthode suppose la radioscopie simultannée de la répartition des particules dans le flux ainsi que des échantillons de contrôle ayant la concentration fixe, et l'exécution de la radiogramme générale. La méthode élaborée est utilisée pour l'étude des profils de concentration dans un flux rapides de gravitation des particules céramiques sphériques sur une pente raboteuse. A l'aide de la méthode radiographique a été contrôlée l'adéquation de la méthode analytique exérimentale élaborée auparavant, qui établit l'analogie formelle entre le milieu granulé du décalage rapide et le gaz dense.