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EXPERIMENTAL INVESTIGATION OF LUMPY COHESIVE LOOSE MATERIALS WITH THE OBJECT OF DETERMINING THE SIZE OF THE OUTLET OPENING OF BUNKERS

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The article examines the determination of the shear characteristics of polydisperse loose materials containing both a cohesive fine fraction and large particles in connection with the problem of calculating the size of the bunker opening.

The physicomechanical characteristics of loose material for calculating the geometrical parameters of bunkers are at present determined in and outside the USSR by Jenicke's method [1, 2]. The method envisages determining the characteristics of loose material on a single-plane shear instrument with yokes of 100-mm diameter.

Regardless of the limited size of the instrument, the author of the method considers it suitable for materials with particles of any size. To determine the characteristics of such materials, it is recommended to test only the fine fraction, separated from the rest of the material by screening it, and the screen mesh may be chosen arbitrarily (e.g., with mesh size of 0.833 mm).

Such a recommendation is based on the assumption that the shear processes in polydisperse loose material occur only through the center of the smallest particles, and that the presence of an arbitrary number of large particles or lumps does not affect these processes at all. No matter what screen is used for separating the investigated fraction, the smallest particles are inevitably contained in it, and the results of shear tests do not change. However, this assumption was not confirmed by experiments specially carried out for testing them. It was found that with decreasing size a of the investigated fraction, the width of

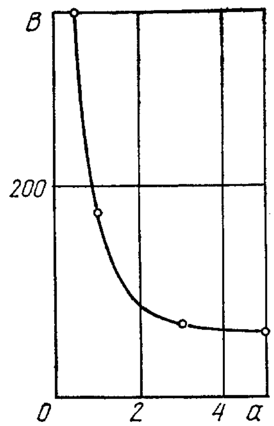

Fig. 1. Dependence of the outlet opening of the bunker on the size of the investigated fraction of loose material. a, mm; B, cm.

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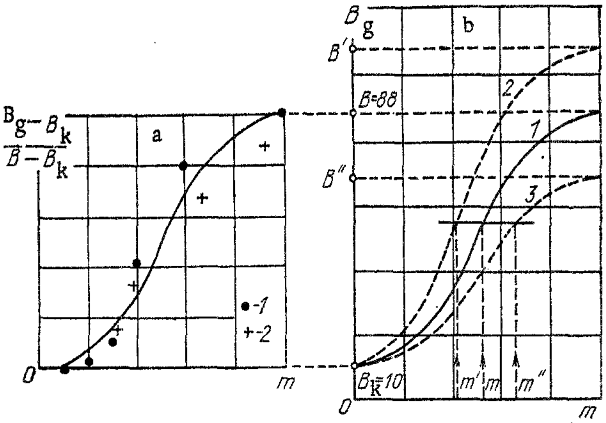

Fig. 2. Dependence of the width of the outlet opening of the bunker on the content of fine fraction in the loose material (*a*: dependence expressed in relative units of measurement): 1, 2) mixtures with particle sizes 10-20 mm and below 5 mm, respectively, of the coarse fraction (b: dependence expressed in absolute units of measurement): 1) fine fraction 3 mm; 2, 3) small fraction finer and coarser than 3 mm, respectively (m, m', m", in true fractions; Bg, Bk, cm).

the opening B does not remain constant but increases considerably (Fig. 1). For instance, the fraction with maximum particle size of 0.5 mm (the 0.5-mm fraction)* yielded a result six times as large as the fraction with the maximum particle size of 5 mm (the 5-mm fraction).

In view of the fact that the result depends on the particle size of the investigated fraction, Jenicke's method is suitable only for such loose materials which can be investigated in their natural state. The same conclusion was also reached by other researchers [3]. It was their opinion that Jenicke's method is suitable only for fine-grained or powdery materials and that it is unsuitable for lumpy materials.

Investigation of lumpy materials (e.g., with particles of up to 300 mm in size) in the natural state requires special large instruments. Because such materials are very widely used in industry, it became necessary to seek ways of simplifying their shear tests. An analogous problem is known in the field of the mechanics of coarse clastic soils. A number of works [4, 5] investigate the physical processes in shear, and it was established there in principle that it is possible to determine the shear characteristics of soils by investigating only the screened-off fine fraction on small instruments.

The present article examines the determination of the shear characteristics of lumpy cohesive loose materials in connection with the problem of calculating the sizes of the outlet openings of bunkers. The investigations were carried out in two mutually independent stages. At the first stage we determined the effect of the percent content of fine fraction in the lumpy material on the size of the outlet opening of the bumker.

The investigated loose material (bauxite) was a mixture of large particles 10-20 mm in size and of a small fraction of 3 mm. Mixtures with 10, 20, 30, 40, 60, 100% content of fine fraction were successively tested. The tests of the material and the subsequent calculations were carried out by Jenicke's method. The diameter of the yoke of the shear instrument (200 mm) made it possible to test the mixture in its natural state. The moisture content of the fine fraction was taken as high as was possible in it, it was maintained the same in all mixtures, and it ensured cohesiveness of the entire mixture.

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*Here and henceforth the expression "fraction *a*, mm" means that it consists of particles whose size does not exceed *a*, mm. This applies to the fractions 5, 3, 2, 1, 0.5 mm.

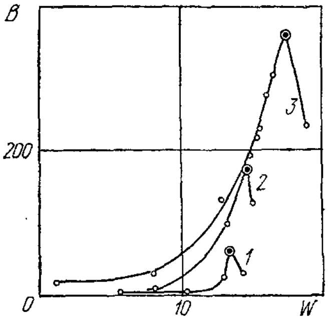

Fig. 3

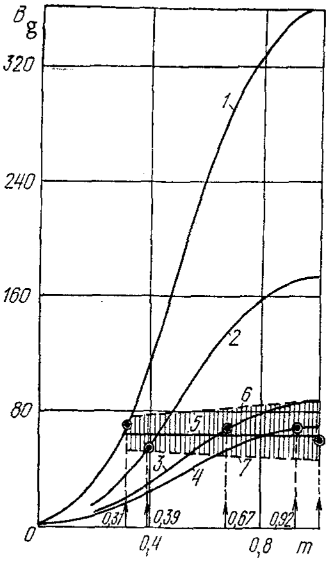

Fig. 4

Fig. 3. Width of the outlet opening of the bunker as a function of the moisture content of the loose material: 1, 2, 3) 5- and 0.5-mm fractions, respectively. W, %.

Fig. 4. Comparison of the sizes B_g calculated from the test results with several variants of the fine fraction: 1) dependence of B_g on m for the 0.5-mm fraction; 2, 3, 4) the same for the 1-, 2-, 3-mm fractions, respectively; 5) dependence of B_g on the size of the fine fraction; 6, 7) boundaries of the 95% confidence interval.

From the characteristics obtained as a result of the tests, the width of the outlet opening of the bunker B_g was calculated for each mixture. The calculated values of B_g are illustrated in Fig. 2a by dots in dependence on m, the content of fine fraction in the mixture. This same figure also presents the results of analogous experiments with four kinds of mixture: the maximum size of the particles in them was 5 mm, and the content of fine fraction m was 0.31 (0.5-mm fraction); 0.39 (1-mm fraction); 0.67 (2-mm fraction); 0.92 (3-mm fraction).

For the various mixtures reduced to one graph (Fig. 2a) and differing by the dispersity of the fine fraction, the sizes of B_g are not expressed in absolute units of measurement as was done in Fig. 2b (curve 1) but in relative units in the form of the ratio $(B_g - B_k)/(B - B_k)$, and as zero of the count we took the value B_k, the size of the opening for a separately taken coarse fraction.

Between the experimental points, a smooth line (see Fig. 2a) was drawn showing the nature of the dependence of the width of the outlet opening B_g for the mixture on its content of fine fraction. This dependence can be expressed in general form by the interpolation formula

$$B_g = B_k + (B - B_k)\,n, \tag{1}$$

where $n = 2m^2$ for $m \leq 0.5$; $n = 4m - 2m^2 - 1$ for $m > 0.5$. The nature of the dependence (1) makes it possible to adopt the two-component model of the structure of the loose material in analogy with the known model of coarse clastic soil [5] which views such soil as a mixture of only two independent components: coarse and fine fractions.

The coarse fraction is the aggregate of strong nonsoaking particles, usually more than 2-3 mm in size. Taken separately, it remains perfectly loose material, no matter what the moisture content is. The material composition of the lumps (granite, iron ore, hard kinds of bauxite, etc.) has an imperceptible effect on the shear resistance of the entire mixture.

TABLE 1. Maximum Values of the Width of the Outlet Opening of a Bunker for the Investigated Samples of Loose Material

Sample	Material in natural state	Fine fractions			
Size of largest particles, mm	5	3	2	1	0,5
Content in material in natural state, fractions	1,0	0,92	0,67	0,39	0,31
Max. width of outlet opening, cm	60	69	88	174	360

The size of the outlet opening of the bunker for a separately taken coarse fraction is calculated in dependence on the size of the largest lump by the formula $B_k = (3-5)a_{max}$ (3 for lumps larger than 100 mm, 5 for lumps smaller than 100 mm).

The fine fraction is the aggregate of fine, soaking, and powdery particles which are usually present in every loose material with complex particle-size distribution. As distinct from the coarse fraction, the shear characteristics of the fine fraction depend to a considerable degree in the moisture content and material composition of the fine fraction. The size of the outlet opening B for the separately taken fine fraction is determined by a method for fine-grained materials [1, 2] on the basis of shear tests on small instruments.

Each loose material is here viewed as a mixture of two fractions characterized by the magnitude m, the percent content of the fine fraction. With m increasing from 0 to 1 (or 100%) the size of the outlet opening of the bunker for the mixture B_g increases monotonically from B_k to B. For intermediate values of m, the value of B_g is calculated by the interpolation formula (1) or it is determined graphically (for an example of such a determination, see Fig. 2b): through point m, a vertical has to be drawn to the axis of abscissas until it intersects line 1. The point of intersection determines the sought size. Such an approach makes it possible to determine the dimensions of the outlet opening of a bunker for loose materials with arbitrary coarseness of the maximum particles without subjecting the lumpy material in its natural state to shear tests.

Viewing loose material as a mixture of two fractions, we have to solve the problem where the boundary between them lies or which fraction has to be considered the fine one. In the mechanics of coarse clastic soils, this boundary is situated around the size of 2-3 mm, and the aggregate of particles smaller than this size is assigned to the fine fraction. Such a division is arbitrary and is not based on specific properties of the particles of this size in particular.

In one of the above-described experiments with several mixtures, the fraction with particles up to 3 mm was taken as the fine one. The selection of this size in particular as fine fraction for the experiment was made arbitrarily. Obviously, if some other, smaller fraction had been chosen, then the size B in Fig. 2b would have increased to some size B', and the graph of the dependence of B_g on m would have taken up the position of line 2, i.e., it would lie higher than 1.

If we take into account that the content m' of this finer fraction is inevitably smaller than m, the content of the fraction with particles up to 3 mm in the mixture, we may assume that the dimension B_g, which has to be determined with the aid of line 2, remains practically at the same level as the one determined according to line 1. The same may be assumed regarding dimension B_g if, conversely, the size of the fine fraction is increased and it is made larger than 3 mm (3, Fig. 2b).

The above assumption makes it possible to formulate the following hypothesis: the width of the outlet opening of a bunker for polydisperse loose material, calculated by the interpolation formula (1), remains invariant with respect to the size of the fine fraction which is taken from this loose material for carrying out shear tests in order to determine the calculation characteristics. The second stage of the investigations had as its object the verification of this hypothesis.

The material in natural state was bauxite with complex grain-size distribution and with maximum particle size of 5 mm. This material was regarded as a two-component mixture of a coarse fraction having maximum particle size of 5 mm and a fine fraction. As the fine fraction, four of its variants were successively examined: sizes 3, 2, 1, and 0.5 mm.

The samples for shear tests were taken in the following manner. First a sample in the natural state was taken by quartering, and the entire remaining material in the natural state was screened by a screen with 3-mm mesh. The oversize material was discarded, and from the screened material (3 mm) a sample of size 3 mm was taken, also by quartering; this was the first variant of the fine fraction. Then the remaining material (3 mm) was screened by a screen with mesh 2 mm, and from the screened material (2 mm) a sample was taken; this was the second variant of the fine fraction (2 mm). Analogous operations were carried out with screens with 1-and 0.5-mm mesh and two more fine fractions, 1 and 0.5 mm, were obtained.

The obtained samples were tested on a shear instrument with yokes of 100-mm diameter by Jenicke's method. In view of the dependence of the shear characteristics on the moisture content, particular attention was paid to ensure conditions of comparability of the results. To attain this, each of the materials was tested with several different moisture contents. For instance, the 0.5-mm fraction was tested with 10 different contents, 1-mm with 4, 5-mm with 5. For each moisture content, the entire complex of physicomechanical characteristics was determined, and the width of the outlet opening of the bunker was calculated. Altogether 520 shear tests were carried out. The widths of the outlet openings for different materials are presented in Fig. 3.

It can be seen from the figure that the dependence of the width of the outlet opening on the moisture content of the material is of an experimental nature and passes through a maximum. The magnitude of the maximum width of the opening and the moisture content corresponding toit are very different for different materials. For instance, with grain size of 5 mm the maximum opening is equal to 60 cm for an experimental moisture content of 13.5% (1 in Fig. 3), and with grain size 0.5 mm it is 360 cm for moisture content of 17.5% (line 3 in Fig. 3).

The investigations of a large number of different loose materials confirmed that the extremal nature of this dependence with a pronounced maximum is found for all investigated materials, and the magnitude of the maximum could serve as a generalized characteristic for each of them. On the basis of this we accepted for further analysis only the maximum values of the width of the opening (see Table 1) of those presented in Fig. 3, and the others were discarded.

The data in Table 1 were the basis for verifying the hypothesis formulated above. Formula (1) was used to determine the width of the outlet opening B_g for material in the natural state, only data on the fine fraction being used, and then the calculated value of B_g was compared with the same width of the outlet opening obtained directly from experimental data with the material in the natural state.

For the fine fraction (0.5 mm) the calculations were carried out with the following data: width of the opening $B = 360$ cm, its content $m = 0.31$ (see Table 1). The width of the opening for the coarse fraction with maximum particle size 5 mm is calculated by the expression $B_k = 5a_{max}$, and it is equal to 2.5 cm. As a result, by formula (1), $B_g = 71$ cm. Analogous calculations were also carried out for the other variants of the fine fraction: 1, 2, and 3 mm, and we obtained, respectively, $B_g = 55$, 69, and 68 cm.

The value of B_g for material in the natural state is equal to 60 cm (see Table 1). Figure 4 shows the determination of B_g for each variant of the fine fraction. First the line 1 was plotted, whichrefers to the 0.5-mm fraction and expresses the dependence of the size B_g on the content of this fraction in the material in the natural state. It was plotted in accordance with formula (1) for the following boundary conditions: for $m = 0$, $B_g = B_k = 2.5$ cm (calculated above); for $m = 1$, $B_g = B = 360$ cm (see Table 1). Since the content of the 0.5-mm fraction in the material in the natural state amounts to $m = 0.31$, the size B_g is determined as the ordinate of the point of intersection of line 1 with the vertical drawn through the point on the axis of abscissas $m = 0.31$.

Line 2 for the 1-mm fraction was plotted for its boundary conditions: for $m = 0$, $B_g = B_k = 2.5$ cm; for $m = 1$, $B_g = B = 174$ cm. The size B_g is determined as the point of intersection of this line with its vertical, whichalready passes through the point $m = 0.39$. Lines 3 and 4 for the 2- and 3-mmfractions wereplotted analogously, and the corresponding points of intersection were determined. On the vertical $m = 1$, the point $B_g = 60$ cm, corresponding to material in the natural state, was marked off.

The aggregate of the ordinates of the points of intersection lucidly characterizes the dependence of the size B_g on the size of the fine fraction that was adopted for the shear tests. It can be seen from Fig. 4 that the ordinates obtained (i.e., the sizes B_g) are fairly close to each other: 71, 55, 68, 69, 60 cm. They fluctuate slightly around the mean value of 65 cm.

To evaluate the dependence of the size B_g on the size of the fine fraction quantitatively, this dependence was approximated by a straight line by the least squares method. We obtained the equation

$$B = 65 - 0.7\,m, \tag{2}$$

in which, instead of the size of the fine fraction, the magnitude m was taken as the argument. Here it was possible to replace the argument because between the two arguments (content of fine fraction and size of its largest particles) there exists a one-to-one correspondence.

The smallness of the coefficient in Eq. (2) – only 0.7 m – indicates that the size of the fine fraction has only a slight effect on B_g. The straight line expressing Eq. (2) (5 in Fig. 4) is practically parallel with the axis of abscissas.

In consequence of the scatter in shear tests, one also obtains some scatter in determining B_g. The dots in Fig. 4 show the mean values of B_g, and from their aggregate Eq. (2) was devised and line 5 drawn. However, each value B_g is characterized by its own confidence interval. Therefore, in addition to the mean values, there are also the aggregates of the maximum and minimum values of B_g which make it possible to plot another two lines bounding the confidence interval from above and from below. In Fig. 4 the 95% confidence interval is bounded by the lines 6 and 7 plotted according to the equations

$$B = 72 + 17\,m, \tag{3}$$

$$B = 59 - 12\,m. \tag{4}$$

A certain widening of the confidence interval with increasing particle size is due to the fact that the scatter of the measurements in the shear tests of the 5-mm fraction is larger than for the 0.5-mm fraction. The variation coefficient of the size B_g fluctuates between 16 and 28%. Such an accuracy satisfies the requirements of practical calculations of the geometrical parameters of bunkers.

NOTATION

a, particle size of loose material; B_g, width of the outlet opening of a bunker for polydisperse loose material; B_k, outlet opening of a bunker for the coarse fraction of loose material; B, B', B", width of the outlet opening of a bunker for the fine fraction of loose material; m, m', m", content of fine fraction in the loose material; W, moisture content of the loose material.

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