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Flow Properties of Granular Sands through a Circular Orifice

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Abstracts□The flow rate of various sand through circular orifice can be measured from a knowledge of a few easily measurable properties of the system. These are the orifice column and particle diameters, the angle of inclination of the orifice with the horizontal and an angle of repose of the granular sand material. Straight lines were obtained when the logarithm of the flow rate was plotted versus the logarithm of orifice diameter. No influence of excessive compaction and bed height was observed and the flow rate increased with decrease of particle diameter. The profile of flow developed the edge of the aperture in a way independent of its size. Linear relationship was observed between the angle of inclination of the orifice and the flow rate.

Keyphrases□Flow rate of sand through orifice–orifice column–particle diameter–compaction and bed height–linear relationship between orifice angle and flow rate.

The need for quantitative information on the variables determining the rate of flow through a restriction has grown with the advent of large scale processes employing moving beds of granular calalyst or other solid.

A great deal of interest exists in the flow of granular solids because of its importance in the flow of tablet granules, coals and cereals.

Deming and Mehring[1] studied the flow rate of a variety of materials through an inverted truncated cone orifice. They reported that flow rate was found to vary with a power of the orifice size and to be influenced by the size and apparant density of the particles, the angle of the materials and cone angle.

Franklin *et al.*[2] also studied flow properties of granular material through a circular orifice and data have been obtained for the flow of granular materials through horizontal and inclined circular orifice.

The variables of importance influencing mass flow rate were the orifice diameter, particle diameter, particle density, and the angle of repose of the material.

Brown *et al.*[3,4] carried out experiments on profile of flow of glass beads, sands through apertures and they found the profile of flow developed from the edge of the aperture in a way independent of its size and shape and there was an empty annulus round the edge of the aperture and the annulus was independent of the size and shape of the aperture.

The present investigation was initiated to study the effect of the following varialbes on the flow properties of sands through a circular orifice: 1) column and orifice diameter, Dc & Do respectively 2) particle diameter Dp. 3) bed height 4) angle of inclination of the orifice cos θ 5) angle of repose, both static and kinetic. Sands were chosen as material of this experiment.

EXPERIMENTAL

Apparatus

Three glass tube columns (internal diameter 2, 1, and 1/2 inch, height 61cm) attaching to each tube in turn the orifice plates with holes 3/8, 5/16, 1/4, 3/16 and 1/8 inch.

Perforated blocking plate ranging from 1/16 inch to 1/2 inch at intervals of 1/32 inch. Repose angle determination apparatus. Balance.

Materials

Silver sand, this is chosen because it had a characteristic shape, and a wide range of size were easily obtainable(80 mesh, 60 mesh, 44 mesh, 22 mesh), particle density, $\rho=2.65$ Gm/cc. Using sieves, silver sands were separated into 85 mesh, 60 mesh, 40 mesh and 22 mesh, respectively.

Determination of Flow Rate

Each of sands, sufficent in quanity to be timed accurately with stop watch, was poured loosely into vertical glass columns and allowed to flow downward through a circular orifice.

The orifice was horizontal and centered at the column bottom except for the runs investigating the effect of angle of inclination from the horizontal. Flow rate was obtained by determining the weight of material flowing in a given time interval, measured by stop watch.

The effect of the angle of inclination of the orifice is from the work of Brown *et al.*[4]

The orifice used were 3/8, 1/4 and 1/8 inch. The orifice plates were mounted at the truncated and of a two inch diameter cardboard tube, for 30° and 60° inclination.

For 90° inclination the orifice was mounted in a side face of a rectangular box of the same diameter as the circular cylinder below which it was attached.

Direct Measurement of the Blocking Apertures Using a Perforated Tray

With the blocking plate in position the sands were poured loosely from a scoop held 3 to 4 times above the tray to produce a fairly level bed which can be finally leveled off with a straight edge.

The blocking plate removed carefully and the size of the largest hole blocked by material was recorded. With a metal rod, the side of the apparatus was tapped allowing material to flow. When flow has ceased, the apparatus was tapped again. The tapping process was repeated until no more flow takes place.

The size of the largest hole blocked was recorded. The size of the orifice which blocks lies in the range from the smallest orifice recorded to one size larger than the largest recorded.

Angle of Repose of Sands

Each of samples was placed on the metal bar (diameter 2 inch) which the aid of column and the column was removed carefully.

The height of the cone of sand was measured by means of a scribing block. To determine the kinetic angle of repose a rotating drum one foot in diameter and eight inches long, was used. The drum could be rotated at constant speeds, from very low rates to about five or six rpm. Kinetic angles were measured with the particle rolling downward over the slanting surface at essentially a constant rate.

The internal kinetic angle could be observed as the plane of contact between the downward moving stream and the stream being carried upward by the motion of the rotating drum.

RESULTS AND DISCUSSION

The results of effects of column and orifice diameter varying column size and orifice size are shown in Table I and Fig. 1.

As seen in Fig. 1, the influence of the wall was negligible. The flow rate increased with decreasing particle size in the same column. Subscript ∞ refers to flow rate through column for which $Dc/Do \rightarrow \infty$. Franklin *et al.*[2] reported that the difference in radii of orifice column in terms of particle diameters is the pertinent variable.

Thus the abscissa expressed as (Dc - Do)/Dp may be more general expression of this effect and he also said that when the difference between orifice and column diameter is greater than about 30 particles diameters, the influence of the wall is negligible and there is an influence on flow rate as orifice and cloumn diameter approach the same value.

In this experiment the largest particle size was one tenth of the difference between orifice and column diameter and the largest difference between orifice and column was 270 particles diameters.

The logarithm of flow rate was plotted against the logarithm of orifice diameter, so that the influence of the orifice diameter is completely satisfied by simple factor. This was shown in Fig. 2.

The slopes of the lines and hence the exponents of the orifice diameter varied with the sands used from about 1.66 to 1.84 with an

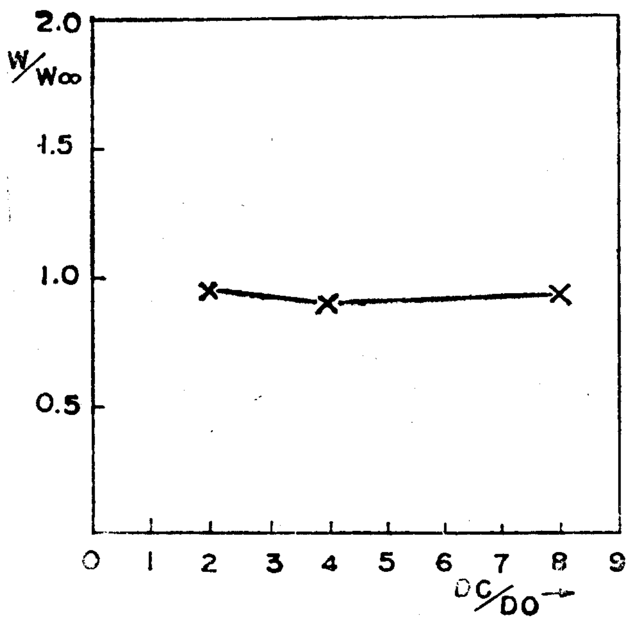

Fig. 1: Influence of container wall upon flow rate.

Table I: Flow rate of granular sands through a circular orifice (Horizontal orifice results)

Material	Dp (cm)	Dc (cm)	Do (cm)	W(g/sec)
Sand 22 mesh	0.0650	2.54	0.9525	19.19
			0.6350	5.77
			0.4763	2.33
			0.3175	0.751
Sand 40 mesh	0.0390	1.27	0.7938	10.68
			0.6350	5.97
			0.3175	0.749
		2.54	0.7938	6.00
			0.4763	2.45
			0.3175	0.811
		5.08	0.6350	6.03
			0.3175	0.888
Sand 60 mesh	0.0250	1.27	0.6350	6.43
			0.3175	0.941
			0.1588	0.141
		2.54	0.6350	6.52
			0.3175	1.00
			0.1588	0.142
Sand 85 mesh	0.0180	1.27	0.6350	6.77
			0.3175	1.00
			0.1588	0.161
		2.54	0.6350	6.05
			0.3175	1.09
			0.1588	0.150
		5.08	0.6350	6.68
			0.3175	1.11

Dp: Particle diameter, Dc: Column diameter, Do: Orifice diameter, W: Flow rate
Each value of W repressents the mean of three determination

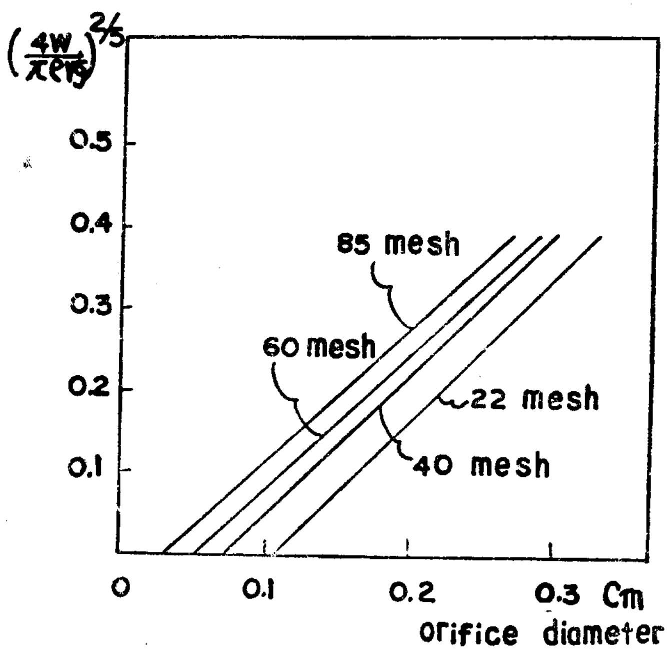

Fig. 2: Influence of orifice diameter upon flow rate.

average value of 1.75. To examine the evidence for an empty annulus adjacent to the edge of an aperture I used the equation of Brown *et al.*[4]

Since granules will not flow through very small apertures, data for rates of efflux are not easily obtained. Therefore the aperture giving rise to zero flow rate can be determined only by extrapolation of the curve of flow rate, W, against aperture size.

For this purpose it is convenient to transform W, or the volume of efflux W/p, into an equivalent length. A simple experiment shows that W is proportional to $\sqrt{\rho}$. Since $W/\rho\sqrt{g}$ has the dimensions of (length) 5/2, we plot

$$L_D = \left(\frac{(4W)}{\pi\rho\sqrt{g}}\right)^{2/5}$$

against the diameter of aperture Do over a range of data for which the graph is linear

$L_D \propto (Do - K_D)$

where K_D is the diameter for which L(or W) is zero. The linearity of the graph in Fig. 3. shows that flow rate is rightly expressed as a function of (Do - K_D).

The intercept can therefore be found reliably by linear extrapolation of the regression line. The values of K_D are given in Table II.

It is important that the intercept K_D does not depend on the size of the aperture. The mean intercept K_D depends, inter alia, on particle size, decreasing 0.106 to 0.034 as the size of sands decreases.

Tray test of 22 mesh sand was also carried out to compare K_D value with the results obtained by tray test. After the range covering the blocked aperture had been noted for the loose packing the tray was struck sharply and repeatly, allowing any flow that ensured to cease before the next tap, until no further flow took place. The data were shown also in Table II.

Table II: Range of Blocked apertures and Width of empty annulus for orifice circles.

Material	Dp (cm)	Range of Blocked Orifice (cm)	K_D (cm)
Sand 22 mesh	0.0650	0.1588 – 0.238	0.106
Sand 40 mesh	0.0390		0.073
Sand 60 mesh	0.0250		0.050
Sand 85 mesh	0.0180		0.034

The K_D values are a little smaller than the diameter of blocked aperture by tray test. Brown *et al.*[4] reported that the smallest circles through which flow could be induced were 2 to 3 times larger than the intercept K_D.

The effect of bed height on flow rate is in Table III and Fig. 4. The column diameter was 2 inch and orifice diameter was 0.25 inch. The minimum height of sand was 3cm from the bottom of the column. Nearly no effect was found with all of the samples. No influence of excessive compaction was found. Franklin *et al.*[2] said that no further correlation could be found provided that the bed height was greater than the height of the cone formed by the moving particles as they approached the orifice or bed height less than one column diameter. But Hinchley[5] had pointed out that one property of granular materials was that their flow through an orifice was a function of the orifice diameter and is practically independent of the head.

Deming *et al.*[1] also found that head was shown to have no practical effect upon the value of flow rate by widely varying the depth

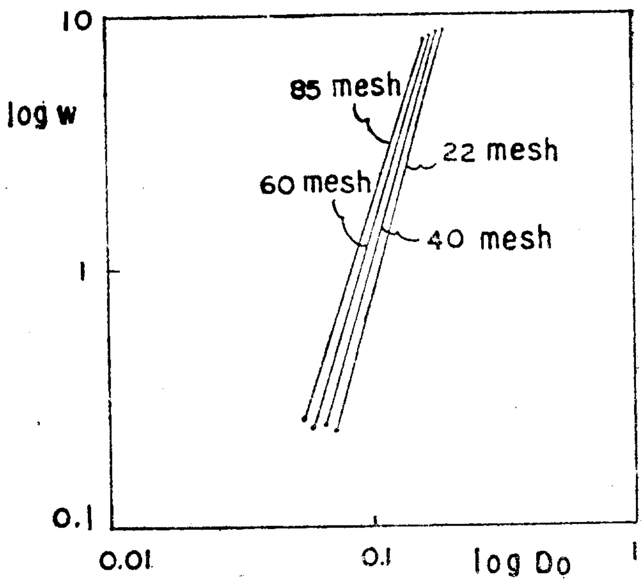

Fig. 3: Influence of orifice diameter upon flow rate.

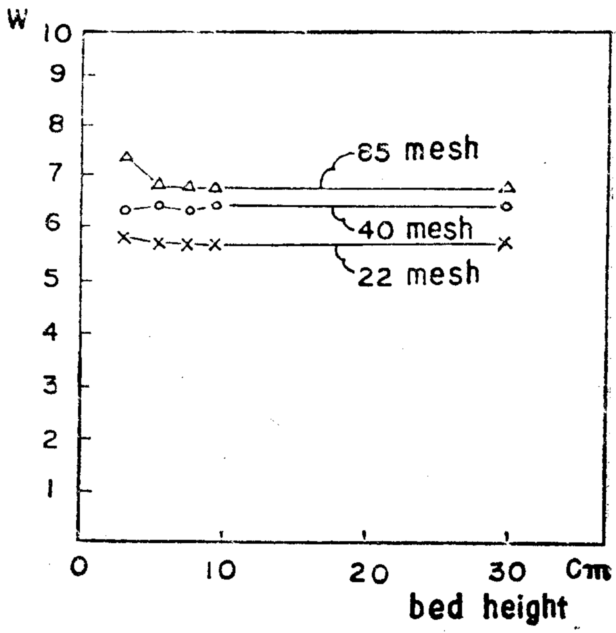

Fig. 4: Influence of bed height upon flow rate.

Table III: Influence of bed height upon flow rate

Material	Flow rate (g/sec) bed height (cm) 3	5	7	9	30
Sand 22 mesh	5.97	5.89	5.85	5.87	5.87
Sand 40 mesh	6.30	6.45	6.33	6.40	6.38
Sand 85 mesh	7.22	6.83	6.77	6.83	6.85

while other factors remained the same.

The effect of the angle of inclination of the orifice was summarized in Table III and illustrated in Fig. 5.

As shown in Fig. 5, the data can be represented by straight lines if mass rate of flow is plotted versus the cosine of the angle of inclination from horizontal of the orifice.

An extrapolation of such lines to intercept the abcissa at zero flow rate suggests that flow rate will approach zero as the axis of the orifice approaches a line perpendicular to the kinetic angle of repose. Deming and Mehring[1] recommend their equation only for cone orifices, of cone angle ranging from 20° to 110°.

The decrease in flow rate with increasing cone angle is not marked, and it would be expected that application of their equation to cone angles approaching 180° or a horizontal orifice, would not be greatly in error.

The angle of repose would appear to be an important characterization factor for less easily defined particle properties, such as shape, roughness, effective void fraction.

According to Franklin *et al.*[2], the use of internal kinetic angle of repose gave a better correlation of the flow rate data than did use of either static or surface kinetic angle. They explained that this may have been due in part to the dependence of surface angle upon the rate of rotation of the drum.

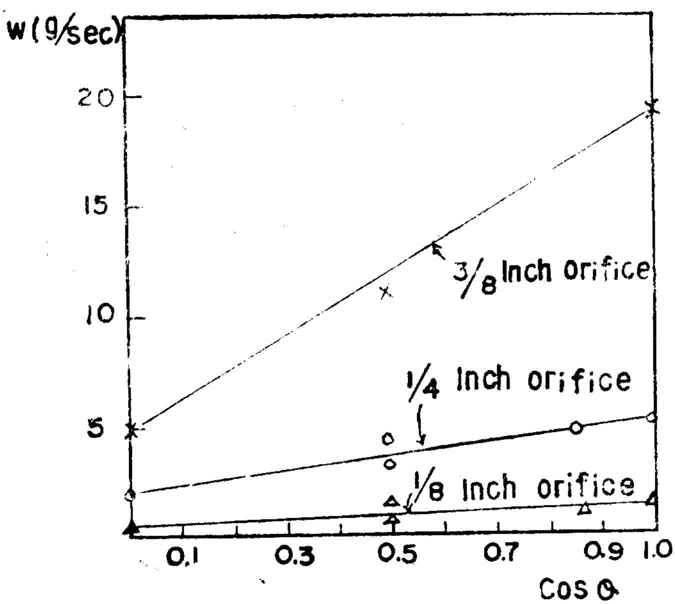

Fig. 5: Flow rate correlation of sand (85 mesh) through inclined orifice.

Table IV: Inclined orifice results

Materials	Do (cm)	Dp (cm)	Angle of Repose	Q = 0°	*Flow rate (g/sec) = 30°	= 60°	= 90°
Sand 22 mesh	0.9525	0.0650	33° 45″	18.77	15.58	9.56	4.37
	0.6350			5.89	4.61	2.75	1.05
	0.3175			0.751	0.575		
Sand 85 mesh	0.9525	0.0180	35° 18″	20.08	16.51	11.23	5.04
	0.6350			6.05	5.56	3.32	1.47
	0.3175			1.11	0.910	0.418	0.109

*Flow rate represents the mean of three determination

Inter-correlation between surface and internal kinetic angle of repose is shown in Fig. 6.

Although this correlation is of adequate precision for this work, it should be accepted with caution in view of the limited knowledge of the factors influencing the various angles of repose.

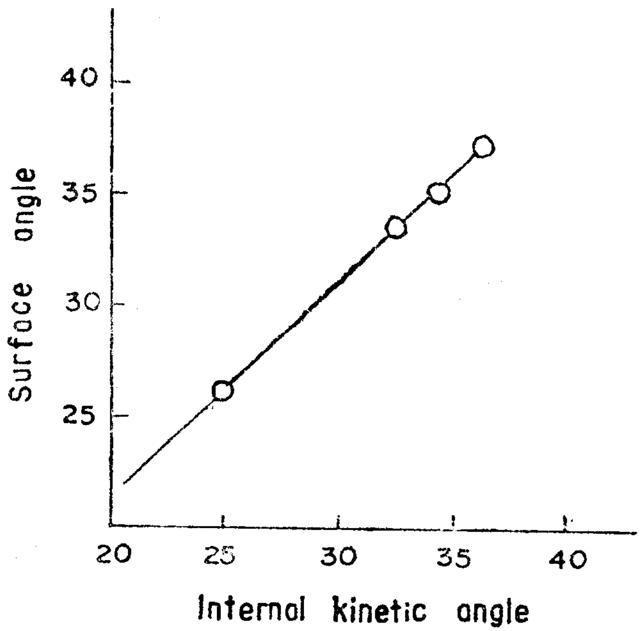

Fig. 6: Inter-relationship of angles of repose.

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