TENTATIVE DATA ON FLOW RESISTANCE IN SUSPENSION CURRENTS

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ABSTRACT

The efficiency with which turbidity currents have carried large volumes of sand for great distances on slight slopes of the deep-sea floor is remarkable. This seems to argue against high flow resistance by "jostle" viscosity and floor impacting. The grading of the deposits is inexplicable by thin, dilute currents because these would have to be fed at the origin over a period of a dozen hours or longer, to supply the observed volume of larger beds, and with decreasing grain size. High densities (over 1.16) seem more probable than great thicknesses (over 100 m). Experiments on viscosity of suspensions showed moderate values up to densities of 1.2 for clay and 1.5 for mainly sandy mixtures. Eddies large in comparison with the grain size do not meet serious obstruction by jostling. Measurements in a circular flume of bottom drag for suspension currents indicate that resistance is less than for clear water on a cohesive rough bottom of the same grain size and less than 2 X that of clear water on a smooth hard floor.

These results, although of a tentative nature and without refinement by considerations of scale or of the paddle turbulence, appear to show that densities over 1.16 up to 1.5 as deduced from velocity cum thickness of the currents and from grading in the turbidites, are not contradicted by flow resistance. True experimental turbidity currents are being studied to gain further insight.

INTRODUCTION

In transportation by flow of water important aspects are bottom drag, viscosity, and turbulence. The possible variations with temperature and salinity are usually ignored by geologists because in most problems they are small compared to the lack of data on current velocity, discharge, bed roughness, grain-size distribution, availability of transported materials, available time, etc.

A prominent influence on transportation can also be expected from the particles in transit. The higher the concentration the greater this influence should be. In a river transporting sand bottom drag exerted on the water is augmented by impacting of saltating grains. Besides turbulence dispersive pressure between the particles is active in raising the load above the bed, and may even become the dominant force maintaining the suspension. Suspended particles cause an increase in effective viscosity. In addition to the terms *molecular* and *turbulent viscosity*, it is here suggested to use "*jostle*" *viscosity* for the influence of suspended particles whether gaseous, liquid or solid. It is mainly through the writing of Bagnold (1954, 1962, 1966) that theoretical insight in these matters and numerical data have become available. But there is also a large volume of data obtained by colloid chemists (Rutgers, 1962).

These factors must play an important part in the spread of sediment over the sea floor by turbidity currents. The distances over which huge volumes of sand have been transported in ancient basins is impressive. The most pertinent evidence, however, comes from the present deep-sea floor. Even on abyssal plains with a slope of less than 0.1% turbidity currents have carried sand and silt for distances of

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1000 to 2000 km building graded beds up to a metre and more in thickness.

Some of the conclusions on transportation by Bagnold and followers appear difficult to reconcile with the oceanological observations. If, as they claim, particle collision (jostle viscosity) limits densities to less than 1.15 and a sand load results in a high drag along the bottom, one would expect a much less effective transportation by turbidity currents. This had led the present author to reconsider available information and deductions and to carry out some further experiments on flow resistance in suspensions and on turbidity currents. The latter are still incomplete and will be treated elsewhere. The writer's lack of mathematical ability has limited the scope of his investigations. He hopes more able minds will take over these subjects.

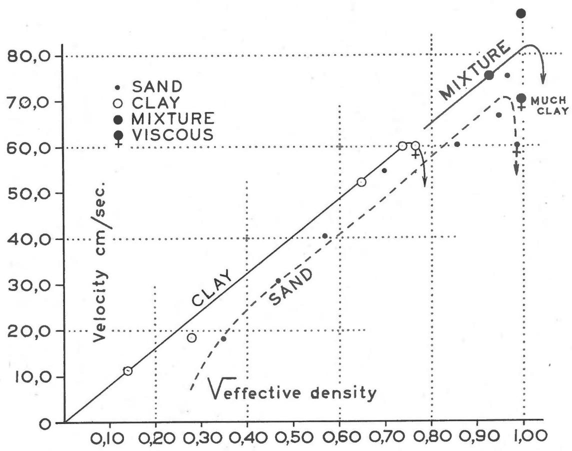

Fig. 1
Relation between velocity and excess density of experimental turbidity currents. Slope $8\frac{1}{2}^{\circ}$, 12 litres (from Kuenen, 1951, Fig. 2).

DENSITY OF TURBIDITY CURRENTS

One of the reasonings developed by Bagnold is that suspended grains hitting the bed are retarded or stopped, and then have to be set in motion again thereby absorbing part of the current energy. On the basis of this postulate it might be held that the upper limit to the sand load of turbidity currents must be low when bottom slope is slight. Data from flume experiments, however rough, should be helpful in evaluating this aspect. Hence, some tests were carried out in a circular flume with suspensions.

But in the case of a turbidity current the mean diameter of the bed particles is about the same as that of the load and there is a wide spread in diameter. This fact, together with the foreward motion and mobility of the bottom surface, added to reduced vertical movements of the particles, render uncertain whether the flow of heavily laden turbidity currents is severely hampered by bottom drag. This drag may not be a limiting factor for density.

Another contention of Bagnold's is that with rising concentration of solid particles the chances of collisions increase. When the space they occupy reaches 9% of the whole space the probability of collisions between spheres of a given size becomes a certainty. The resistance to flow is then much greater and increases very rapidly with further increase in concentration. Komar (1969) on the strength of this reasoning put the upper limit of turbidity currents at 9%, which corresponds to a density of 1.147 for a quartz-grain suspension. Bagnold limited speculation concerning the Grand Banks turbidity current to 10% (density 1.16).

There are several independent reasons for doubting the validity of this conclusion.

(1) In experiments with turbidity currents and suspension currents in a flume the writer (Kuenen, 1951) achieved densities of 1.5 and higher that did not lead to any obvious obstruction to the flow. Fig. 1 shows results of velocity measurements and there is no retarding effect of particle collisions counteracting the velocity increase due to higher density. This holds even in dense clay suspensions in salt water in which the floccules occupy more space than would an equal amount of quartz. Quartz-sand grains can settle out individually to the bottom provided the thixotropic setting does not produce a solid. In the case of a silty commercial pottery clay from Brunssum the maximum density at which this happens is found to be 1.2 (Kuenen, 1966). Yet in the experiments the flow was not hampered by even higher concentrations. Those experiments may perhaps not be representative but it is surprising that the higher viscosity of such suspensions did not produce the marked effect one would expect.

(2) The lutum concentration (<30 μ) in turbidites can be used to find the density of that material in the suspension (Kuenen, 1966). To find the density of the depositing current the transported sand must be added. By this method current densities of 1.2 and higher in marine turbidity currents were deduced. If

the source contained a high proportion of sand such as to be expected on the delta of a swift river, then the excess density of the suspension should have been greater than the deduced lutum density, hence higher than 0.4.

(3) Another reason for assuming high densities is that less water need be set in motion, and that a current of great thickness need not be assumed in order to explain high velocities. The dispersal of sediment to levels of several hundreds of metres is then not required, rendering the initiation of the current less of a puzzle.

(4) The volume of some oceanic turbidites is gigantic; for the Grand Banks 1929 current of the order of 50 to 100 km^3. With a low density the depositing current would have to continue flowing during a day or even days, much longer than it can have taken the current to reach the abyssal plain. It then becomes hard to understand what the feeding mechanism was, and harder still to account for the grading to the deposit. A continuously fed current cannot produce grading (Kuenen and Menard, 1952).

(5) The knolls on the basin floor of the Gulf of Mexico were not topped by the turbidity currents building up the abyssal plain (Ewing et al., 1958). This limits the current thickness to less than 100 m. The levees of submarine canyons provide a minimum thickness for the currents of about 100-150 metres (Kuenen, 1951; Griggs and Kulm, 1970). But the fine-grained composition and the fact of deposition indicate that the main, swift part of the larger flows, even in the confined space of a canyon, was less thick, hence of the order of 80-100 metres as a maximum. Turbidity currents do not appear to use spill-ways out of abyssal basins until the latter are filled with sediment. Hence, deep-sea topography favours current thicknesses well below 100 metres.

In summary, the low bottom slope, large distances covered, the huge volumes transported, the grading of the deposits, the sudden initiation by an earthquake shock, the evidence against great thickness of the flows, together bear witness in favour of high densities. Values upwards of 1.2 are indicated, although naturally less than the density of the sediment prior to movement, which may be of the order of 1.8. Values above 1.15 (240.000 p.p. million) are so much higher than what is usual in rivers and are beyond Bagnold's postulated limit. For these the term "high density" is justified. The uncertainty whether currents of high density actually occur calls for new evidence. Two lines of experimental testing are explored in the present paper: viscosity and bottom drag.

Menard (1964) has also assumed that the density of turbidity currents is limited. Although he did not specifically state an upper limit, his treatment uses the value 1.1. Menard presents 4 reasons for questioning high densities. (1) Low initial density of sediment before being set in motion. This objection only holds for certain localities, but bears no weight against high densities in most cases. (2) Observed natural turbidity currents have very low densities. But as these were generated by rivers in reservoirs they do not set limits for slide-generated currents in the sea. (3) The experiments by Kuenen were not made with currents of high density. Menard ignored the earlier experiments in a tank, where the velocities were measured immediately after release, with initial densities up to 2.0 (Kuenen, 1950). In the later ditch-experiments the method of sampling with a syphon must have tended to under-evaluate density (intake upwards at right angles to current, some water penetrates before sample is taken, intake partly from above sampling level and from behind nose). As values of 1.27 were found at 2.5 metres from the point of release, the tests show convincingly that currents flowed some distance while parts retained densities over 1.3. The shallow water and confined conditions of these experiments must have favoured turbulent mixing and presumably the small scale has had the same influence. In later experiments in a circular flume (Kuenen and Sengupta, 1970) suspension currents were produced at over 3.5 m/sec with densities up to 1.5 that did not appear to be hampered by this heavy load.

The case for turbidity currents with densities of 1.2 and higher appears to be strong enough to warrant a critical look at the main counter arguments: viscosity and bottom drag.

EXPERIMENTS ON VISCOSITY OF SUSPENSIONS

Bagnold (1954) carried out a number of experiments on suspensions of spherules with density equal to that of water dispersed in Newtonian fluids of varying viscosity (water and glycerine-water-alcohol mixtures) all of density one. The suspensions were contained between two concentric drums of which one (usually the inner one) was rotated. Radial dispersive pressure and torque on the stationary drum were measured for volume concentrations of the spherules (diameter 130 microns) between 13% and 62%.

The stringent requirements of these admirable experiments restricted their practicability to one grain size and to spheres only. The outcome has resulted in the opinion that one should not speculate on turbidity currents of densities beyond 1.16 if high velocity and persistance of flow on slight slopes are accepted aspects of natural occurrences. It therefore appeared useful to perform some further tests that allow observations on a wide range of grain sizes and mixtures and of different shapes under entirely different conditions to those achieved by Bagnold. The experimental arrangement used in the present series of tests is much less sophisticated and provides less fundamental data. But the results may help understanding how natural turbidity currents can flow fast at high sediment concentrations.

The actual measurements were made with a commercial viscometer[2] showing the torque exerted on a suitable shaped body being rotated at a constant speed in the fluid to be tested. The scale is from zero to 100, three velocities can be chosen: 200-64-20.48 rev. per minute. Mostly 200 was used, but for more viscous liquids the torque had to be measured at the middle velocity of the meter. In most cases the values thus found had to be multiplied by 3 to obtain the equivalent data for the higher meter velocity. The fluid was contained in a closed circuit driven round by a propeller (plastic model of ship's propeller). Activation of the propeller was by an a-synchronous motor with squirrel cage armature with transformer variometer. Variometer values are proportional to voltage but not equal; in the present case scale number 100 corresponds to 85 volts. Propeller velocity in this type of motor depends partly on the voltage used and partly on the resistance offered to the rotation. The volume of liquid used was 6.5 litres. The shape of this container together with the propeller and the viscometer are shown in fig. 2. Two grids suppressed the circular motion induced by the propeller so that a steady more or less homogeneous current flowed upwards on the left side where the measurements were carried out. The velocity of this flow was measured for clear water using a neutrally buoyant float, see fig. 3. The still-water level was always the same, because experience showed that both higher and lower positions resulted in less efficient propeller action. The rotated body consisted of a short length of perspex tube covered on the in-

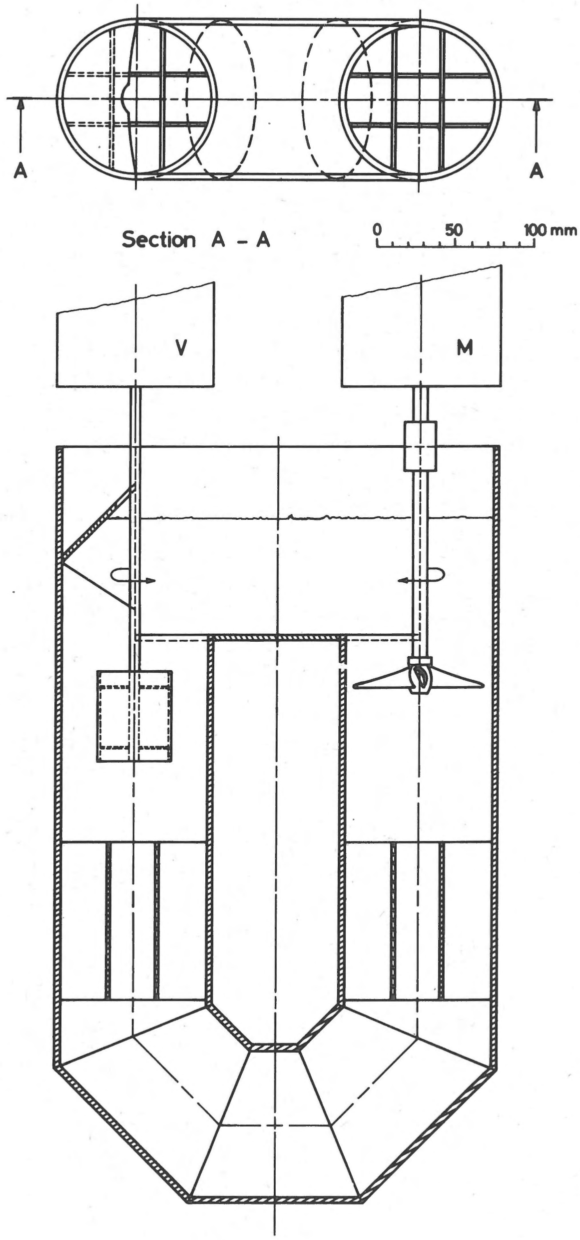

Fig. 2
Section of container used for viscosity measurements. M = Motor + Propeller; V = Viscometer + cylindrical body.

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[2] Epprecht-Rheometer S.T.V., Contraves Zürich.

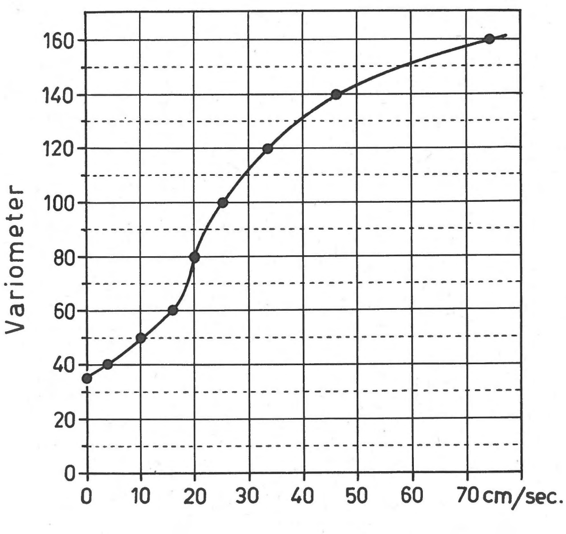

Fig. 3
Relation between transformer values (Variometer) and current velocity of water in container.

and outside with a layer of sand stuck on. It will be assumed that the measurements were all performed with turbulent suspensions, closely similar to conditions in turbidity currents.

The force exerted by the viscometer is partly used to overcome friction, hence a measure of viscosity, but partly also to entrain liquid. The mass thus set in motion is about constant when the current is zero so that only the frictional component remains. But it augments with increasing rate of flow. Hence, the torque is seen to grow together with the speed of the propeller. When the variometer reading is set out against the torque on arithmetic scales a straight line

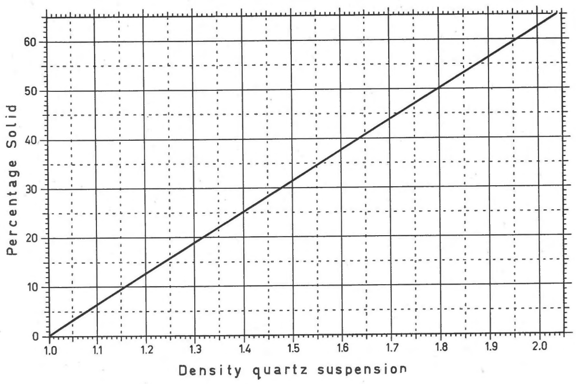

Fig. 4
Relation between volume percentage of solid and density of quartz suspension.

results that starts from the torque value for zero velocity of the propeller at variometer 35. This straight line relation holds for water, waterglass, not too viscous oil, dilute clay suspensions and dilute suspensions of grains.

This circumstance is helpful in cases where a current is needed to keep the particles of higher density than the liquid in suspension. The straight line then found between higher and lower velocities can be extrapolated to find the value for zero velocity.

But when the liquid is more viscous flow does not start until the propeller has acquired some speed. The extrapolation to lower current velocities just referred to, should in those cases be halted at the point where the circulation stops. The procedure becomes more uncertain where fall-out of particles at lower velocity starts to lessen the concentration while flow is still continuing. The torque value for zero velocity at full load of the suspension must then be estimated.

Fig. 5 shows a number of graphs from which zero velocity torque is deduced. Uncertain extrapolations are given in dashed lines. In fig. 6 the zero velocities thus ascertained are set out against the concentrations of solids in the suspensions.

It should be remarked that for clay suspensions in fresh and salt water size, density, and shape of the particles or floccules are not known. It can even be shown that the density of clay floccules in salt-water suspensions depends on the amount of clay per litre of water. Hence, the volume percentage occupied by solids cannot be taken as a basis for comparison. This is the main reason for expressing the results in liquid densities as if homogenized (fig. 4). An additional advantage is that a direct comparison is possible with the excess density of turbidity currents. However, in the tests using plastic or a liquid of higher denstiy than water the true density was recalculated to "equivalent density" which signifies the density of a quartz-water (or quartz + clay-water) suspension with equal volume of solids.

The following results were obtained. Addition to water of magnesium sulphate, waterglass, and clay all raise the torque values. The influence of silt-free china clay is about double that of a silt-rich pottery clay (from Brunssum in The Netherlands). Addition of sand-size particles also raises the torque values, but much less than does the same weight of clay. In a saturated solution $MgSO_4$ (density 1.24) with plastic spherules the rise is negligible below equivalent density of 1.48. In waterglass, density 1.22, the rise

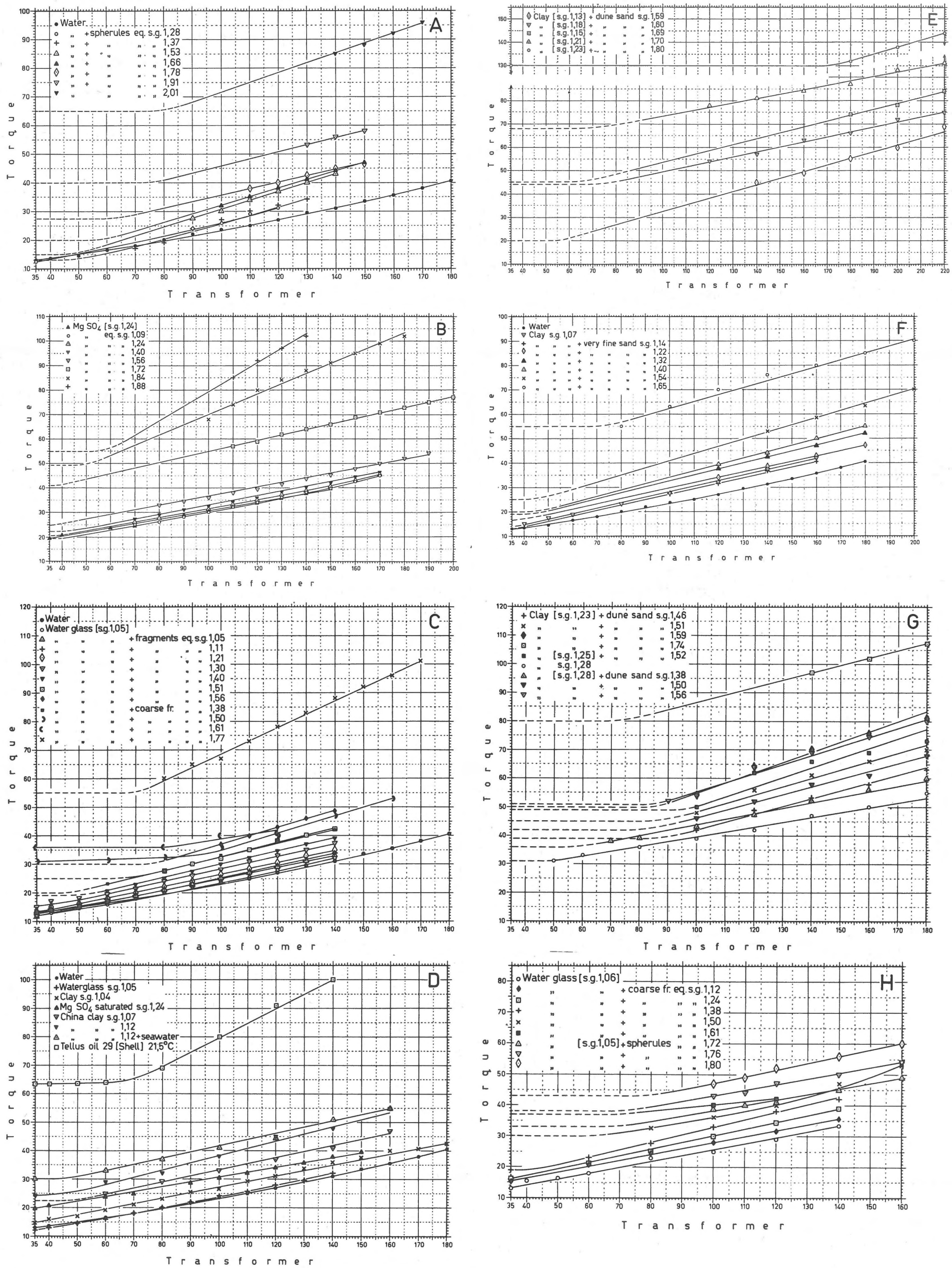

Fig. 5
A to H. Relation between torque and transformer values. Extrapolation to zero current; when doubtful dotted line.

with plastic spherules is steep, especially above equivalent density 1.45; for density 1.19 the rise is slightly less steep up to equivalent density 1.2 and the steep rise comes above 1.55. For density of waterglass 1.05 spherules have no measurable influence below equivalent density 1.25 and the steep rise comes gradually around 1.6.

Spherules in water do not manifest their influence below equivalent density 1.35 and the steep rise comes gradually around 1.8.

For silty clay (Brunssum) the rise is moderate up to density 1.20, but then runs up steeply to 1.28 – the highest tested – where it is 2.5 x that of water (455 gr per litre). For china clay a steep curve is found, starting to rise at low concentrations. Addition of salt (3% NaCl + 0.5% $MgSO_4$) causes a slight increase of torque, especially after several hours standing. It should be noted that china clay doubles the viscosity of water at denstity 1.15, Brunssum at 1.23, spherules at 1.75. The higher the viscosity of the liquid (or fine suspension, like clay) the more influence the addition of silt- or sand-sized solid particles has.

The combination of clay suspensions with fine and medium sand was mainly studied for high concentrations of clay (1.2 to 1.3) because in dilute suspensions the sand settled out too easily. The resulting viscosities are higher than for more dilute clay suspensions of equal equivalent densities. With clay suspensions of density < 1.1 the viscosity is raised to double that of clear water by addition of sand causing a density of about 1.5.

The influence of size is for larger particles to cause higher torque values, but the difference is small and overshadowed by the viscosity variations of the suspending clay water. In fig. 9 dune sand [median 210 microns] [3] and two fine Quaternary sands [medians 165 (Yde) and 85 (Piccard) microns] [3] are seen to have almost equal influence on the shape of the curve. The coarser dune sand is better rounded, however, and would have had more influence if the shape had been the same as of the finer sands. Broken plastic rods in diluted waterglass also show a slight increase of torque values with size of particles. The cause is partly due to the large size causing arched packings in the annular space around the measuring

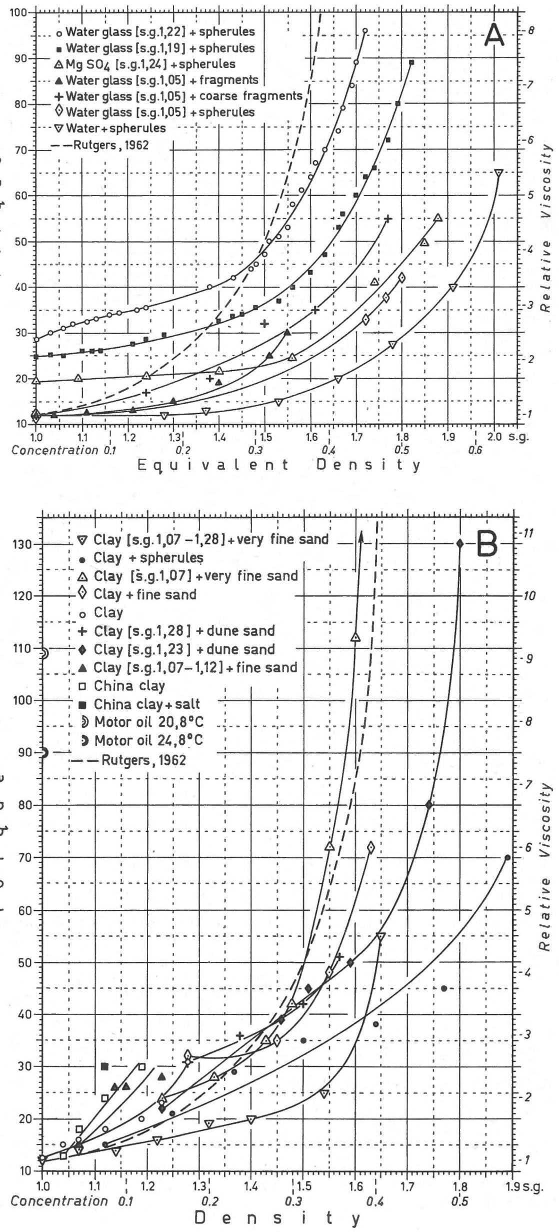

Fig. 6
A,B. Relation between torque at zero velocity. Relative viscosity as shown on the right relates to clear water (torque = 12) and equivalent density of suspension, or volume percentage of quartz.

cylinder. This follows from the unrest of the torque pointer.

The influence of shape is larger than of size. Spherules have less influence than broken rods of about equal size. Hence, normal flow did not become

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[3] For grain-size analyses see K u e n e n and S e n g u p t a, 1970, fig. 5, p. 98.

impossible until a higher concentration of spherules than equivalent density 2.0 (or 63% by volume) was tested. For broken rods small amounts had some influence and 40% by volume or equivalent density 1.64 formed the limit for normal flow. For equivalent density 1.7 spherules show 3 x and rods 4 x the viscosity of clear water.

From the matrix of deep-sea sands and non-metamorphic flysch turbidites the density of the clay suspension in the forward parts of the current was estimated for several cases as 1.1 (Kuenen, 1966). Even at density 1.2 (assuming a significant proportion of silt) the viscosity is still hardly above twice that of water. Adding sand to give densities of 1.4 still leaves the viscosity close to that of water. Below densities of 1.55 due mainly to non-flocculating particles viscosity can hardly be considered important for seriously limiting velocity. Its main influence will be to lessen small-scale turbulence.

A comparison can be made with results of chemists for relative viscosities of suspensions. Rutgers (1962) drew an average curve for many data pertaining to spheres ranging in size from a few hundred microns to far below 1 micron. Much higher values were obtained than in the present tests as can be seen in fig. 6A, in spite of the absence of turbulence. However, in the clay suspensions of fig. 6B the coincidence with the general curve of Rutgers is remarkably good, especially for the one with very fine sand.

A rough impression of the viscosities found by the present tests can be obtained by comparison. Silty clay shows a torque value of 40 at density 1.3. Mixtures of clay at density 1.1 with sand attain 40 at combined densities of about 1.5. to 1.6. This compares with torque 13 for water and torque 108 for Shell multigrade X-100 at 21°C and torque 90 at 25°C. The viscosity of that oil is three times that of a turbidity current of density 1.4 with a moderate clay content.

The solid concentration of 9% (equivalent density 1.14) for spherules is claimed by Bagnold as more or less an upper limit for turbidity currents. For irregularly shaped particles the same reasoning would apply at 8% (equivalent density 1.12).

The present measurements do not support this view. If viscosity were a limiting parameter it could not become significant below density 1.4. The point at which rising viscosity might outweigh the accelerating influence of rising density should hardly be expected below 1.6. Even then, this would not constitute an upper limit to density but only to velocity.

The general conclusion can be drawn that speculation on the density of turbidity currents need not be limited by considerations of jostle viscosity. Possibly the velocity obtained by application of Chezy's formula may be too high if viscosity has an influence on the value of the constant. But still, up to lutum densities 1.1 and total densities 1.4 the formula can be safely used, without taking jostle viscosity into account (see also fig. 13).

EXPERIMENTS ON BOTTOM FRICTION OF SUSPENSION CURRENTS

The experiments on bottom friction were carried out on suspension currents in a circular flume. Earlier tests with this instrument were directed towards understanding turbidite ripples (Kuenen and Humbert, 1969) and furthermore aimed at data on suspension (Kuenen and Sengupta, 1970). The present test treated two aspects, lag of the water compared to the paddles, and the pressure on the paddles under varying conditions of velocity and suspension.

A *Lag of the water*

In the first place measurements were carried out to find the lag of the water compared to the centre of the sixteen evenly spaced paddles.

The paddle velocity was taken by stopwatch, usually 10 revolutions. For the water velocity a small plastic bottle filled with water was rendered almost neutrally buoyant with a few sand grains. At low velocities it tended to stay below the paddles and to register the velocity at an average of about 10 cm from the floor, but at 60 cm/sec, the lowest velocity examined in most of the earlier tests on suspension of particles, the bottle not only hit the bottom from time to time but also rose to the surface now and then and swung from the inner to the outer wall. It should give a reasonable value for the average velocity. Differences between separate measurements of the time for 10 revolutions of the bottle usually amounted to no more than one or two per cent.

The lag of the water in per cent of the paddle

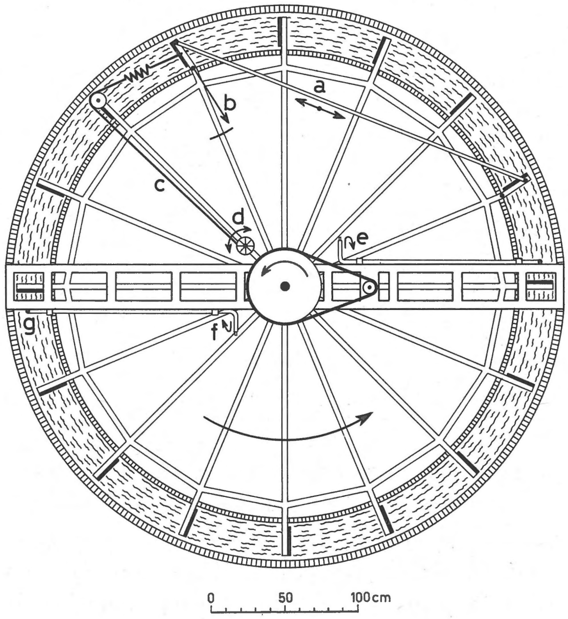

Fig. 7
Circular flume seen from above. Two connected (a) paddles can pivot to measure force exerted, zero position shown by (b). Wire (c) connected to measuring spring, (d) toothed wheel. Remote controls (e) (f) (g).

velocity (at centre of paddle) was roughly the same for all speeds examined, with perhaps a slight tendency to increase with the current velocity.

cm/sec	16	33	60	110	180	250	300	350	375
lag in %	2.7	1.1	3.8	7.4	4.9	5.8	5.2	5.6	6.2

Former experiments on suspension had been carried out, like the present tests on lag, with a depth of water of 56 cm, and the paddles dipping 34 cm. Tests were now also made of the lag with lowered water level and with the paddles raised, giving the following results for the average of all speeds, lag in per cent.

normal	water level	water level	water level	paddles raised			
dip 34 cm	– 6 cm	– 11 cm	– 16 cm	5 cm dip 29 cm	10 cm dip 24 cm	15 cm dip 19 cm	20 cm dip 14 cm
3.4	4.0	5.4	6.6	3.4	4.8	7.5	11.3

These values show that raising the paddles 5 or 10 cm or dropping the water level 5 cm do not have much influence on the lag of the water. From this it was tentatively concluded that if the paddles were made to dip only about 20 cm their number would have to be doubled. The net result should be roughly the same lag, but the undisturbed part of the current below the paddles would be increased from 22 to about 36 cm. The slope of the water surface at high velocities limits the possible reduction of dip to an amount of about 12 cm, corresponding roughly to 48 paddles.

To test the influence of this alternative arrangement of the system a comparison was made between the functioning with 16 paddles dipping 33 cm and with 32 paddles dipping 17 cm, water depth 55 cm. Five samples were taken at velocities 360, 240 and

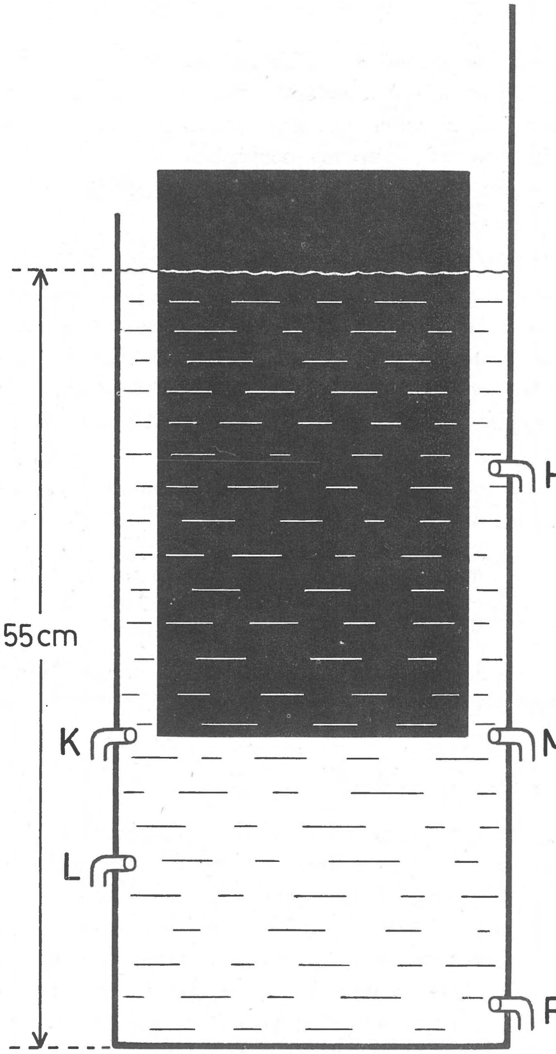

Fig. 8
Section of circular flume with sampling points and outline of paddle.

TABLE A
Amounts in suspension > 32 microns in grams per litre.
A = 16 paddles dipping 33 cm; B = 32 paddles dipping 17 cm.
Density suspension < 32 micron; s.g. = 1.022.

Sampling point (fig.)	Velocity 360 cm/sec		Velocity 240 cm/sec		Velocity 85 cm/sec	
	A	B	A	B	A	B
H	206	188	138	113	25	17
M	240	243	184	174	27	29
F	278	259	210	209	32	32
K	311	293	247	276	41	51
L	314	345	298	360	50	65
Average	270	266	215	226	35	39

85 cm per second. The filling of the flume was about 450 kg of mixed sand and 50 kg of china clay. The lag of clear water was also ascertained for the two conditions of the driving mechanism.

Table A shows the amounts in suspension at the five sampling points of fig. 8.

From table A it follows that the average amount in suspension is roughly the same for both arrangements. However, with the 16 paddles the vertical distribution is more equable, the 32 paddles showing greater concentration towards the bottom. Condition A applies to the experiments described in Kuenen and Sengupta (1970).

The lag with arrangement B (32 paddles dipping 17 cm) for clear water is as follows:

cm/sec	10.5	16	21	27	37	47	66	83	105	125	144	162	183	200	213	230	239	261	319	383	396
lag in %	0	3	2	1	2	3	4	1	0	1	4	4	4	5	4	4	2	6	3	6	6

This is 5/7 of the lag with 16 paddles dipping 34 cm. The difference is hardly significant.

B *Energy expended*

The energy expended by the paddles to cause flow and turbulence at a given velocity was measured by a kind of spring balance shown schematically in fig. 7. Two of the sixteen paddles at 90° from each other were each mounted on a vertical axle 9 cm long and held by two ball-bearings attached to the driving spokes. The axles were positioned just above the inner wall of the flume. The two paddles were connected to each other by a thick nylon cord or a light plastic tube so that they moved conjointly. The foremost of the two paddles had an arm extending 50 cm inwards above the spoke (b in fig. 7), the upturned end running along a scale of 10 cm length. The middle of this scale indicated that both paddles were accurately aligned with the corresponding spokes of the driving wheel. This meant that they were then exerting the same pressure as each of the 14 fixed paddles.

In the middle of the upper edge of the foremost paddle an eye was attached to which a spring could be fitted with a wire at the other end running to a pulley on the next spoke. This pulley was placed so as to ensure that the force exerted by the spring was at right angles to the mobile paddle in mid position. The other end of this wire c was carried round a vertical axle d on the spoke near the centre of the flume. It had sufficient friction to remain in a fixed position when the spring was exerting its maximum pull of about 5 kg. By turning this axle the wire could be made to regulate the tension on the spring until the paddles were aligned with the spokes. Naturally, the faster the current the higher the tension had to be.

As the adjustment of d had to be carried out while the driving mechanism was in action, a simple kind of remote control was applied. To the top of axle d a disk was fitted with eight vertical, radially positioned plates (= teeth). A pin at the end of an arm with a handle g was attached to the bridge across the flume bearing the driving mechanism of the paddles. The pin could be held horizontally, as shown in the drawing, then being inactive. It could also be turned down in a position in which it caught behind one of the teeth of d as the latter revolved with the paddles. The axle d was thereby wound 1/8 of a revolution.

With each revolution of the paddles the spring was tightened by such a stroke, amounting to 7.5 mm of shortening of the wire c. If the spring was tightened too much and the paddle pulled beyond a neutral position, as shown in the drawing, the axle d could be wound back a stroke by lowering the pin e which engaged at the opposite side of d.

The reason for linking two paddles was that the breadth of the flume varied slightly from place to place and as a result the water velocity was not constant all the way round. This caused the pointer to swing back and forth by an amount equivalent to several per cent of the pull when only one paddle was mobilized. The connected paddles showed much less swing. There then remained no uncertainty which tooth to choose for aligning paddles with spokes. It was even possible to estimate half strokes. For the maximum velocities a single tooth represents 3.7% of total tension.

Measurements were carried out as follows. At a given paddle velocity the pull on the spring was increased by the action of e until the marker b reached the mid-point. In this position the mobile paddles were exerting the same pressure on the water as the fixed ones. The position of d was visible because the teeth were coloured differently. This position gave the amount the spring was extended and as the spring had been callibrated the tension was then known. Multiplication by 8 gave the total pressure exerted on the water by the driving mechanism and multiplication by the velocity of the central point of the paddles showed the total energy being given off. This could be expressed as a value per metre length of the flume measured along the circle over the middle of the paddles.

Three springs of different strength were tested. The pull of the weakest increased by 50 grams for each tooth of d, by 100 gr for the middle spring, and by 165 gr for the strongest spring. Fig. 9 shows that the tension in the three springs at equal water velocities correlated satisfactorily. Because it was not possible to set the motor accurately at a chosen speed, the velocity of the paddles was measured each time a new test was made. The period of acceleration of the water was a matter of seconds.

Fig. 9 also shows that 10° centrigrade difference in temperature does not have a measurable influence on the pressure exerted per paddle.

In fig. 10 and 11 the relation is shown between velocity and the pressure in kg exerted per metre

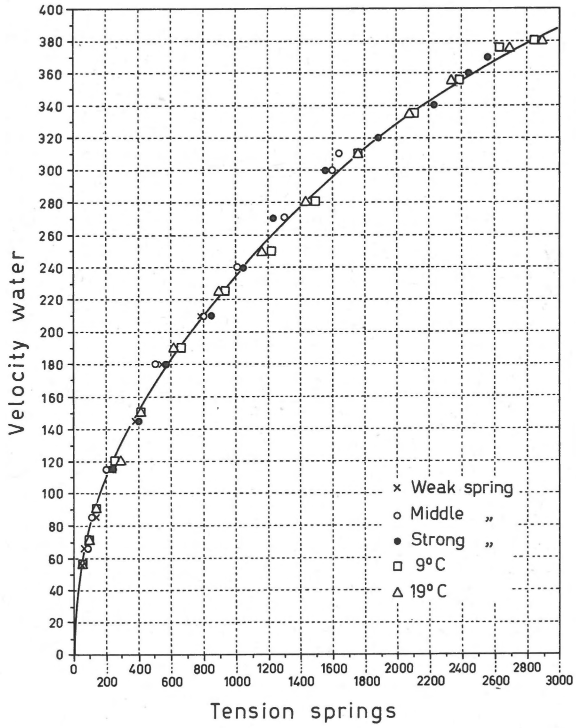

Fig. 9
Relation between water velocity in cm/sec and tension of three springs with one mobile paddle, and with strong spring, at two temperatures of the water. Bottom with stuck-on sand.

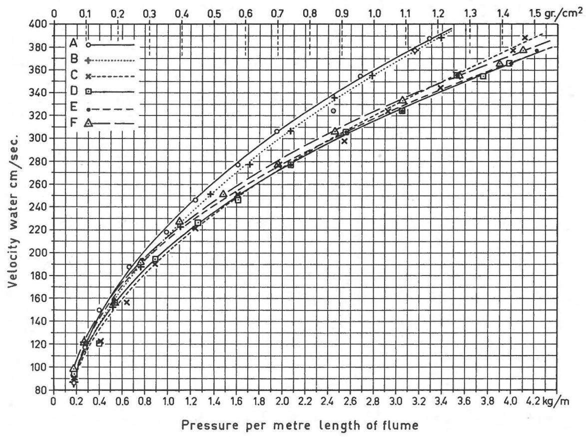

Fig. 10
Relation between velocity of water and pressure in kg per metre length of flume (depth 55 cm). A = clear water on smooth bottom; B = 150 kg dune sand (= 88 gr/litre; s.g. 1.05); C = roughened floor, clear water; D = 150 kg dune sand (88 gr/litre; s.g. 1.05); E = 300 kg dune sand (= 177 gr/litre; s.g. 1.11); F = 450 kg dune sand (= 265 gr/litre; s.g. 1.16).

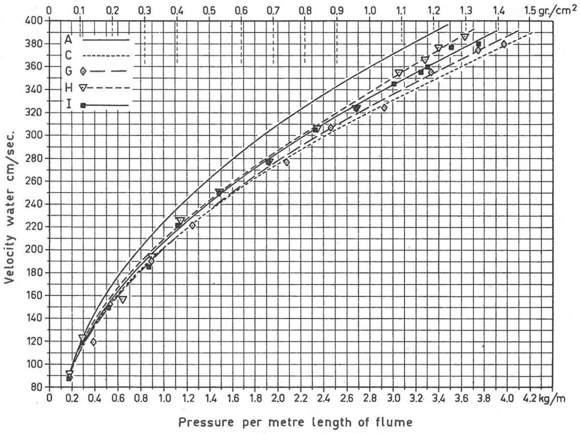

Fig. 11
Relation between velocity of water and pressure in kg, per metre length of flume (depth 55 cm). A = clear water on smooth bottom, C = roughened floor, clear water, G = 150 kg coarse sand (= 88 gr/litre; s.g. 1.05). H = smooth bottom, 100 kg china clay in sea water, excess density 0.035; I = 200 kg china clay, excess density 0.07.

length of flume or in grams per square centimetre under various conditions. A is for clear water and a smooth bottom (sand layer smoothed over with araldite = epoxy glue). In B 150 kg of dune sand has been added (well rounded, median diameter 220 micron). In C clear water is again used, but here the floor has been covered with a layer of coarse sand (750-1200 micron) stuck on with araldite. In D, E and F dune sand has been added, 150 kg, 300 kg, 450 kg respectively (spread out evenly this would form layers 2.5., 5 and 7.5 cm thick on the floor). In G there is 150 kg of coarse sand (200-2000, median 400 microns) on the roughened floor. In H and I the bottom has again been smoothed, and suspensions have been used of Cornwall china clay of 100 kg and 200 kg respectively in the 1700 litres of artificial sea water, excess densities 0,035 and 0,07 over the clear sea water.

In judging the results it should be born in mind that the floor is about 1/5 of the wetted perimeter. It is assumed that the suspended sand causes no increase in friction along the walls. Changes caused by bottom roughness and load should therefore be related to 1/5 of the force required for clear water on a smooth bottom. Part of the energy is consumed by the turbulence around the paddles, but no correction for this has been introduced.

The following tentative results are obtained.

1) On a smooth bottom the addition of dune sand had most influence at middling velocities. The increase in per cent for the given conditions was at its maximum 70% at 140 cm/sec; the absolute maximum increase was 0.1 kg/metre or 0.036 gr/cm² at 260 cm/sec. As more and more sand was lifted into suspension and more of the smooth floor was uncovered the difference in exerted energy decreased. At 380 cm/sec when all the sand was in suspension the increase was 0.4 kg (= 0.14 gr/cm²) or 6%. Weight increase due to the 150 kg dune sand used was 5%.

2) The coarse layer stuck to the floor caused an increase of no less than 130% at 380 cm/sec, and 155% at 300 cm/sec, 110% at 140 cm/sec.

3) *Adding* finer, rounder sand on the roughened floor caused a *decrease in friction*, the effect increasing with the amount of sand. The maximum drop measured was 88% of the bottom friction on a rough cohesive floor at about 180 cm/sec. When most of the finer loose sand had been taken into suspension the friction was equal to that without extra sand (at 305 cm/sec for 150 kg, at 320 cm/sec for 300 kg, at 350 cm/sec for 450 kg) because then its smoothing effect on the bottom had disappeared. It ended up with becoming slightly greater, 23% at 380 cm/sec.

Three points are indicated in fig. 8 and 9 where the whole charge of the flume had gone into suspension. One would expect that when the current

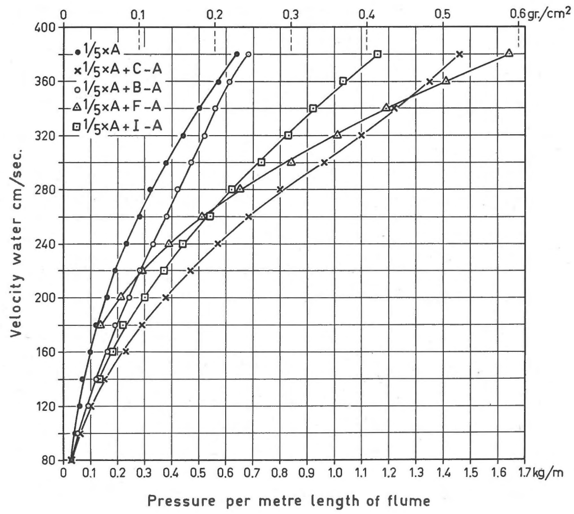

Fig. 12
Relation between water velocity and calculated drag on floor in grams per square centimetre or in kg per metre of flume.

has raised all sand from the bottom the larger amount would cause the greater increase in friction. The experiments indicate that the opposite is the case, but the cause could be inaccurate measurement. One possibility, if the effect is real, could be the development of a carpet below a more heavily loaded current, but no visual evidence of such a feature was detected. Another possibility – the most attractive one – is that in a denser suspension there is less turbulence resulting in less steep trajectories of the saltating grains. This should result in less resistance.

4) The introduction of coarse angular sand (fig. 11, G) on the roughened floor caused some reduction in friction, but less than the fine sand at low velocities. At higher velocities this loose coarse material still reduced the bottom friction by 10%.

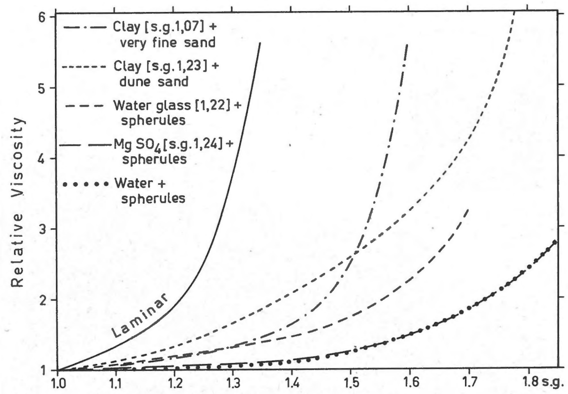

Fig. 13
Main results on viscosity.

5) The clay-salt water suspensions caused a marked increase in energy requirement, slightly greater for the denser suspension. Presumably this is a result of higher viscosity. The data suggest that at velocities above 320 cm/sec the divergence from the clear water current started to diminish.

INTERPRETATION OF THE RESULTS

Fig. 13 summarizes the results of viscosity measurements. In several respects the circular flume currents differ from turbidity currents. In nature the side walls are missing, the spiral flow caused by the curved shape of the flume is absent, the extra turbulence around the paddles is lacking, the surface is not an abrupt interface with air, but a thick stratum with gradually upward decreasing velocity and density.

Another flaw in the tests is that current velocity was only measured for clear water. It has been assumed that the lag with relation to the paddles is the same for the suspensions. A float with a tracer and a detector could have been used to verify this assumption, but this refinement was not carried out. The tests are more of qualitative than quantitative value anyhow on account of the other imperfections mentioned. The writer – with his lack of mathematical ability – has not attempted a closer analysis of the factors involved, or a quantitative application to estimates on turbidity currents. The following conclusions are of a tentative and qualitative nature only.

Addition of loose sand on a smooth bottom caused the greatest increase in drag at middling velocities, because at higher speeds more and more of the smooth bottom was swept clean. At a concentration of 90 grams per litre (density 1.054) and a velocity of 380 cm/sec the bottom drag was increased 6%, against 70% at 140 cm/sec when the floor was still covered. Obviously the major factor at this concentration is bottom roughness.

At a certain moment a grain will be sufficiently retarded to join the moving coat of grains on the bottom. The current will then lose the propellent force of gravity exerted on that particle, but because no previously stationary grain need be set in motion the remainder of the moving matter will not be deprived of energy.

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Plate I
Circular flume with 16 paddles, glass walls, two siphons in centre of foreground (later replaced by tubes through plexiglass wall). Sand ripples under settled-out china clay.

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