

EXPERIMENTAL MARINE SUSPENSION CURRENTS, COMPETENCY AND CAPACITY

PH. H. KUENEN¹⁾ and S. SENGUPTA²⁾

ABSTRACT

In a circular flume (diameter 4 m) suspension currents were generated with various kinds and concentrations of clay (lutum) and sand. Starting from maximum velocity (230 or 300 cm/sec) samples were drawn off at successively lower velocities at three levels. The amount in suspension coarser than 33 microns was measured and for a number of representative cases grain size analyses of these sands were made. There is an increase in median and amount from the higher to lower levels. At current velocity of 48 cm/sec particles smaller than 38 microns are not concentrated towards the bottom. At higher velocities there is even concentration upwards in some cases for grains smaller than 150 microns. The results demonstrate that the concepts of competency and capacity are strongly interrelated, the grain size distribution of the load in suspension depending on the original charge placed in the flume.

The deposits tended to show log-normal distribution, the steepness of the cumulative curve depending on the composition of the suspension. All grain sizes in suspension were involved in the deposit forming. This was not due to current fluctuations and only partially to entrapment of fines between coarser grains. The coarser the fraction the more is abandoned relatively. For this reason the remaining suspension does show a decreasing median. The lutum greatly increases the carrying power, especially for finer grain sizes, the strongly flocculated Wadden Sea lutum having the greatest influence.

The quantitative results are presumably roughly applicable to the lower part of turbidity currents. However, the exchange with higher levels is excluded in the experiments, and the paddles cause increased turbulence. Spiral flow is

another drawback. For the deposition of a bed with median size of 200 microns, a velocity of 2 to 3 metres is required, for a median of 1 mm (that is to say a gravelly turbidite) something of the order of 10 m/sec, much depending on the concentration of lutum. At rippling velocity, about 50-60 cm/sec, the median of the deposit is around 80 microns.

There appears to be no or only insignificant exchange between deposit and current in so far as concerns the grains that have become immobilized. No flutings or groovings develop during the process of deposition. Even while rippling is going on there is no or only slight local erosion. The climbing ripples of many turbidites with deposition on the stoss-side betoken non-erosion. No indications of the existence of a traction carpet were found or observed, a circumstance that is attributed to the absence of grains larger than those carried all the way in suspension.

I. INTRODUCTION

In rivers sediment transport has been studied, mainly by water sampling to ascertain the suspended load. The reason is that bottom transport is difficult to assess. Flume studies on the other hand have concentrated on bottom transport, partly to amplify the fluvial data, partly because the length of a flume is too small to ensure equilibrium between bottom and fine-grained suspended load. Moreover, the handling of clay-sized matter presents problems and observation is hampered.

Tests in sea water have been scarce. Menard (1950) performed experiments in a marine channel. Einstein and Korne (1962) used a recirculating flume with fine sediment in salt water, but the churning action of the driving mechanism limits the applicability of results. As ancient sediments in

¹⁾ Geological Institute, University of Groningen, Melkweg 1, Groningen, Netherlands.

²⁾ Geological Studies Unit, Indian Statistical Institute, Calcutta, India.

general and turbidites in particular are largely marine and partly or entirely deposited from suspension, there is an urgent need for basic information from laboratory experiments on marine suspension currents.

The senior author, partly following Postma, showed (K u e n e n, 1965, 1966a, 1966b) that a circular flume (circular in groundplan, not in section) provides a closer approach, in some respects, to natural flow over large distances than other types of instruments. It is especially effective for high-density suspension currents to furnish data for understanding turbidity currents. Admittedly the spiral flow and churning action of the paddles are disadvantages. The spiral flow appeared to decrease upwards gradually and to die out about 20 cm below the surface.

Former experiments by the author in circular flumes were intended to throw light on horizontal lamination, on the formation of current ripple mark under varying conditions, and on the lutum content of turbidites. More insight was obtained concerning the deposition and erosion of clay in sea water at lower current velocities and the maximum concentration that can show turbulent flow. Regressive sand waves were produced at higher velocities.

A suspension current in a flume differs from a turbidity current because the overlying stagnant water is missing. But it does appear legitimate to consider the current as closely equivalent to the lower part of a turbidity current. Admittedly vertical exchange is limited by the upper surface of the flume current. Hence, the equivalent of the bulk of the turbidity current is missing. Circumspection is evidently needed in the interpretation and the application of experimental results to turbidity currents in nature. But in the absence of any samples taken from natural turbidity currents, the present values for suspension currents can provide a starting point. In a separate paper (K u e n e n and H u m b e r t, in press) it was shown that current ripple mark in natural turbidites and in circular flume experiments show a remarkable degree of similarity in grain size distribution, thus vindicating the use of this instrument for testing certain aspects of turbidity currents.

The aim of the present investigation is to gather data on capacity and competency of, and deposition from marine suspension currents at variable velocities and with a wide range in lutum densities. Data on frictional resistance were also obtained. These will be published separately.

II. EXPERIMENTAL ARRANGEMENTS

The flume used in this investigation has an outer diameter of 390 cm, the channel is 30 cm wide, 59 cm deep on the inner wall and 74 cm on the outer wall. Sixteen paddles carry the water round with a speed that can be varied from a few cm/sec to almost 400 cm/sec (Fig. 1 and 2).

Water velocities were determined for clear tap water at various paddle speeds. A neutrally buoyant float (small plastic bottle) was carried along by the water. It tended not only to rise and fall, but also to revolve anywhere between the inner and outer walls, so that it demonstrated what the average velocities in the water were, but of course not the discharge. By counting one or two dozen revolutions the difference in velocity between the centre of the paddles and the average in the water was roughly obtained. It was found that the lag amounted to 1 per cent at low velocities rising to 7 per cent at maximum speed.

At first both walls were made of 16 bent panes of glass 6 mm thick, the floor covered with paint. The volume when filled to 55 cm was 1750 litres. Samples were taken through siphons. One was close to the inner wall just above the highest level to which sediment accumulated (22 cm from floor). Because of

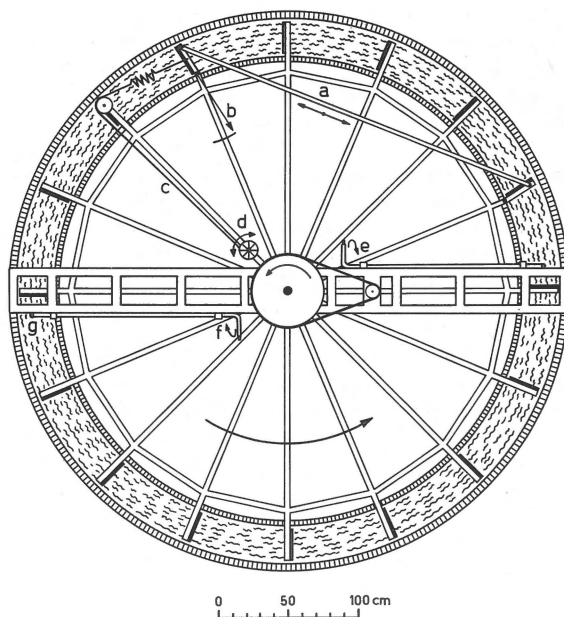


Fig. 1
Diagram of the circular flume used in the experiments, seen from above (with arrangement for measuring pressure on the paddles, a to g, not used in the present study).

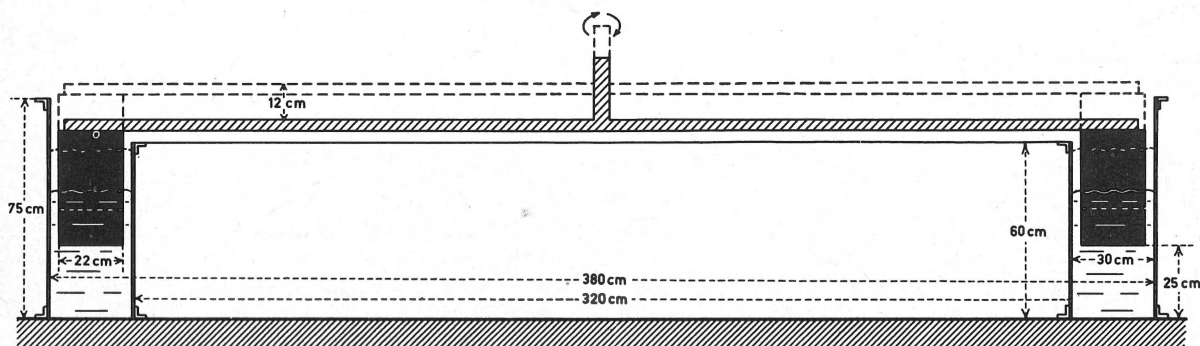


Fig. 2
Diagrammatic section of the flume.

the spiral flow which rises against the inner wall, the sample is representative of the current close to the bottom. Two siphons were placed near the outer wall, one 10 cm below the surface (for stagnant water depth 55 cm), the other 21 cm from the bottom. The copper tubes were bent horizontally at the end in the direction against the current, and had an inner diameter of 12.5 mm (Fig. 3). Samples were always taken after the siphons had been allowed to run a short time into a bucket.

The volume of the samples (500 to 800 cm^3) was determined, the lutum was then washed out on a 33 micron sieve and the dry weight of the remaining silt plus sand ascertained. The density of the clay suspension was calculated from the amount of clay used, or it was measured after the current had flowed overnight at 32 cm per second, a velocity which allowed sand and coarse silt to settle out but kept flocculated clay and fine silt in suspension. The artificial sea water was made by adding 30 gr NaCl and 5 gr MgSO_4 per litre of tap water. The densities of the clay suspensions given are values in addition to the density of clear sea water, the data on silt and sand as dry weight above the size of 33 microns. The velocities tested varied between 300 or 230 and 48 or 28 cm/sec, assuming that the lag with respect to the paddles is the same as that in clear water. With each new charge of sediment or change of clay suspension a new experimental number was adopted. First maximum velocity was applied until no more sediment was lifted from the bottom. In many cases all sand was raised at velocities far below the maximum. The erosional period lasted only a few minutes. A few minutes later the first samples were taken and the

velocity was then decreased. A period of adjustment was allowed before the next batch of samples was drawn off. The lower the velocity and the higher the lutum density the more time was allowed for the overloading of the current to disappear by fall-out. By watching the deposition and by comparison of samples taken at intervals a minimum adjustment period for each velocity was determined. For 48 cm/sec half an hour sufficed and for 28 cm/sec an hour.

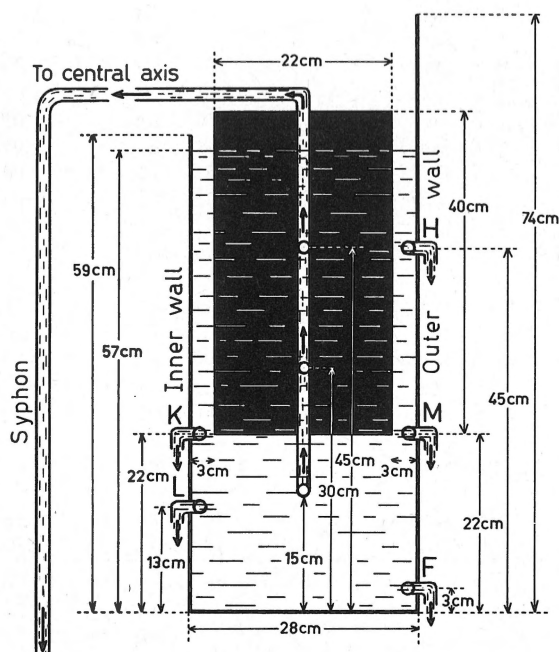


Fig. 3
Section of channel showing sampling points.

TABLE I

Charge placed in the flume

Exp. number	water level	kg < 33 micr. Mainly clay	Density lutum	Charge > 33 micr. kg*) gr/litre			Density total
1	F D = 54 cm	Trace	1.00	280 C	40E	175	1.11
2	F same	7.5 Ch	1.003	same	same	same	same
3	S same	same	same	same	same	same	same
4	S same	17.5 Ch	1.007	same	same	same	same
5	S same	50 Ch	1.018	same	same	same	1.12
6	S same	75 Ch	1.026	same	same	same	1.13
7	S same	125 Ch	1.044	same	same	same	1.15
8	S same	175 Ch	1.062	same	same	same	1.17
9	S same	275 Ch	1.10	same	same	same	1.20
10	S same	same same	same	450 C	same	280	1.26
11	S D = 44 cm	220 Ch	same	same	same	327	1.29
12	S D = 31 cm	195 Ch	same	same	same	505	1.40
13	F D = 54 cm	190 Ch	1.075	same	same	280	1.24
14	F same	160 Ch	1.06	same	same	same	1.22
15	S same	same same	same	same	same	same	same
16	S same	133 Ch	1.05	same	same	same	1.21
		7 Bt					
17	S same	133 Ch	1.055	same	same	same	1.22
		22 Bt					
18	S same	120 Ch	1.06	same	same	same	same
		20 Bt					
		15 Pt					
19	S same	90 Ch	1.057	same	same	same	1.21
		15 Bt					
		50 Pt					
20	S same	30 Wa	1.013	same	same	same	1.17
21	S same	60 Wa	1.024	same	same	same	1.19
22	S same	104 Wa	1.039	same	same	same	1.20
23	S same	80 Wa	1.031	360 C	50 D	90 E	285
24	S same	28 Wa	1.011	same	same	same	1.19
25	B D = 30 cm	18 Wa	1.016	same	same	same	523
26	S D = 54 cm	185 Mi	1.08	same	same	same	285
27	S same	170 Mi	same	same	same	same	470
					300 F		
28	S D = 40 cm	same same	1.12	same	same	same	646
					300 F		
29	S D = 42 cm	same same	1.11	same	same	same	790
					300 F	180 G	
30	S D = 54 cm	same same	1.09	same	same	same	576
					300 F	180 G	
31	S same	90 Mi	1.05	same	same	same	same
					300 F	180 G	
32	S same	30 Mi	1.016	same	same	same	same
					300 F	180 G	
33	S same	? Mi	1.02	A+B+C+D+E+F+G			440
34	F same	Trace	1.002	Mixed			325

F	fresh water	A	loess
S	salt water	B	sloef (mixture of little clay and much silt)
B	brackish water	C	Pleistocene sand of doubtful nature
D	depth of water	D	idem
Ch	china clay	E	idem
Bt	bentonite	F	coastal dune sand
Wa	Wadden-sea lutum	G	Rhine river sand
Mi	mixed clays		

* For composition see Fig. 5.

TABLE IIA

Load of samples > 33 microns in gr/litre

Experiment	Level	1	2	3	4	5	6	7	8	9	10
Velocity/cm/sec											
230	H	141	123	129	134	140	—	151	159	165	258
	M	168	166	168	167	170	—	169	169	158	261
	L	227	222	217	216	204	—	198	188	170	277
190	H	101	91	108	96	113	120	136	151	160	350
	M	144	125	142	136	156	163	165	168	164	258
	L	198	195	207	201	213	209	202	169	175	269
135	H	46	41	47	40	63	—	80	110	153	244
	M	75	66	73	75	90	—	113	140	159	260
	L	112	111	122	119	137	—	159	179	180	266
80	H	13	11	12	13	16	—	34	55	113	182
	M	17	20	19	20	25	—	50	78	128	215
	L	36	37	37	38	46	—	69	107	141	231
48	H	4.1	4.5	4.7	6.2	6.9	11	16	26	54	58
	M	7.1	8.3	7.3	8.7	11	15	20	29	55	59
	L	12	14	13	14	16	21	24	33	58	60
32	H	0.5	0.6	0.6	0.8	0.8	0.8	0.6	0.5	—	—
	M	0.5	0.7	0.7	0.8	1.0	0.9	0.3	0.9	—	—
	L	0.7	1.2	0.8	1.2	1.2	1.1	0.5	0.6	—	1.9

TABLE IIA

Load of samples > 33 microns in gr/litre (continued)

Experiment		11	12	13	14	15	16	17	18	19	20
Velocity cm/sec	Level										
230	H	304	—	253	228	244	—	229	254	240	223
	M	310	435	257	258	263	—	252	249	253	265
	L	321	450	272	290	268	—	264	264	273	295
190	H	305	—	233	—	214	—	206	224	218	202
	M	315	421	258	—	250	—	244	251	227	251
	L	329	455	273	—	280	—	273	273	278	311
135	H	294	—	213	102	143	414	163	162	151	100
	M	—	438	247	166	189	204	214	208	200	158
	L	322	455	278	227	249	259	264	260	252	220
80	H	238	—	134	—	67	57	66	57	51	32
	M	249	333	174	—	96	93	97	92	79	51
	L	267	349	200	—	125	117	124	116	108	73
48	H	45	—	57	15	31	25	27	27	23	12
	M	44	—	61	20	33	31	30	22	31	16
	L	40	—	65	24	39	33	33	29	36	20
32	H	—	—	0.6	0.9	—	0.1	0.1	0.1	1.8	1.7
	M	—	—	0.6	1.0	—	0.3	0.1	—	—	1.9
	L	—	—	1.0	1.3	—	0.1	0.1	—	—	2.4

TABLE IIA

Load of samples > 33 microns in gr/litre (continued)

Experiment		21	22	25	26	27	28	29	30	31	32
Velocity cm/sec	Level										
230	H	241	243	—	275	378	—	—	438	368	245
	M	247	239	410	265	426	558	677	506	479	405
	L	265	251	467	279	468	588	688	582	—	573
190	H	229	246	—	255	284	—	—	388	258	128
	M	250	254	—	256	337	553	670	473	386	219
	L	272	262	—	279	472	587	686	550	516	386
135	H	178	222	—	217	267	—	—	147	81	67
	M	215	243	146	253	362	551	643	189	123	112
	L	267	249	191	285	417	543	677	253	217	194
80	H	74	187	—	149	134	—	—	143	56	21
	M	102	209	—	187	153	247	320	150	87	34
	L	128	220	—	192	168	256	345	173	117	78
48	H	30	62	—	43	38	—	—	43	32	9.8
	M	36	63	—	43	39	8.2	39	47	37	13
	L	39	64	—	42	43	8.0	36	48	46	21
32	H	1.7	1.2	—	0.4	2.6	—	—	1.2	0.9	0.6
	M	2.1	1.0	—	0.4	4.9	1.8	3.2	—	0.7	1.0
	L	2.2	0.9	—	0.3	4.4	—	—	—	1.6	3.2

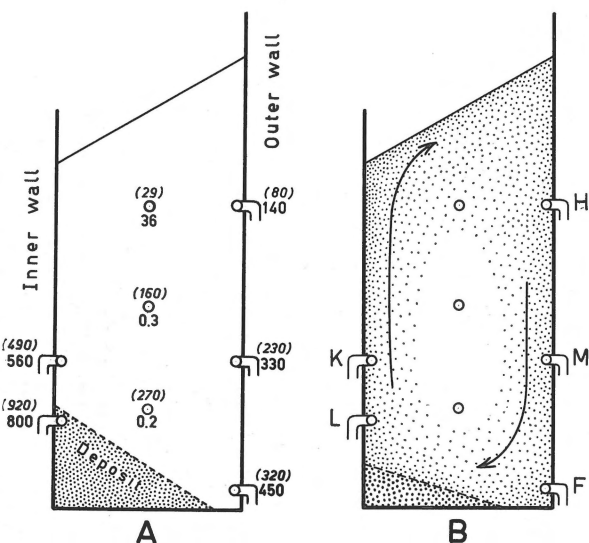


Fig. 4
Position of sampling points in cross section; three in the middle were fixed to three paddles. In the experiments before 33 the siphons took samples at H, M and L. The density in grams per litre are shown for a test at two velocities, at 340 cm/sec and 300 cm/sec between brackets. The average load was somewhat over 200 gr/litre. At the higher velocity the sediment was concentrated along the periphery in the manner shown in diagram B.

This procedure of starting from highest velocities ensured that the currents were always loaded to capacity and competency in so far as the charge of the flume sufficed. Neither could the deposits contain material protected from erosion by coarser deposits of an earlier test.

While the experiments were being carried out increasing trouble developed with cracking of the glass. Finally, after Exp. 32, the glass was replaced by perspex 16 mm thick. Bucarite, a kind of plastic putty, was used for fixing combined with screws. The floor was made of a sheet of plastic. Although the channel was still not perfectly shaped it was so much improved and strengthened that a higher velocity was now possible up to 370 cm/sec. The breadth was now 28 cm, the working volume 1700 litres. It was also possible to bore holes in the plastic walls to insert tubes for sampling. Five holes were made in the positions shown in Fig. 4.

At these higher velocities the samples showed a density of sand suspension far in excess of the average calculated from the charge of sand placed in the

flume¹ Evidently the sand was concentrated along the walls. To test this deduction siphons were installed at three levels, each on one paddle. Because of the centrifugal force the siphoning action decreased with increasing velocity. Hence, the outflow end of the siphon, below the central axis of the paddle wheel, had to be held as low as possible. Changing the shape and direction of the intake made little difference. At the highest velocities it cost a lot of trouble to obtain representative samples, the water surface being only 107 cm above the floor.

These paddle samples confirmed that the centrifugal force and spiral flow concentrated the sand almost entirely along the periphery of the cross-section. The central parts of the current were practically free of sand and medium silt.

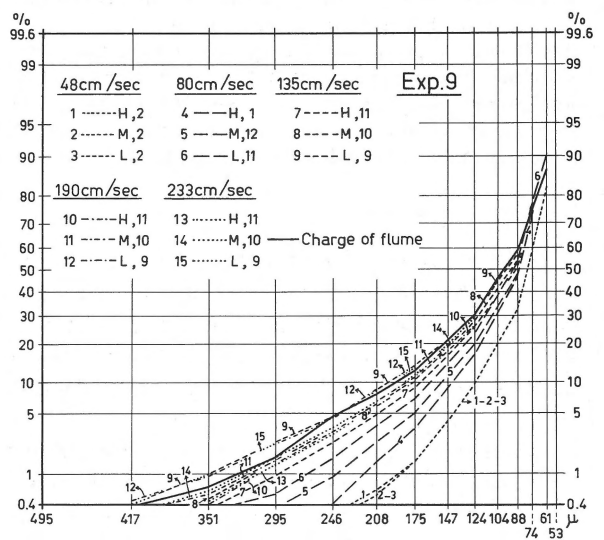
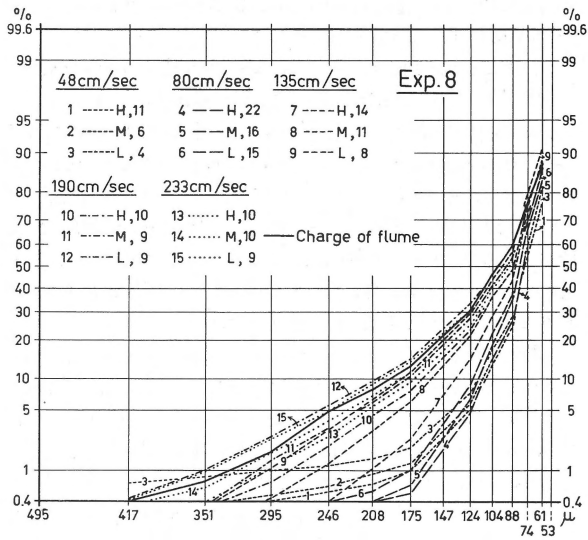
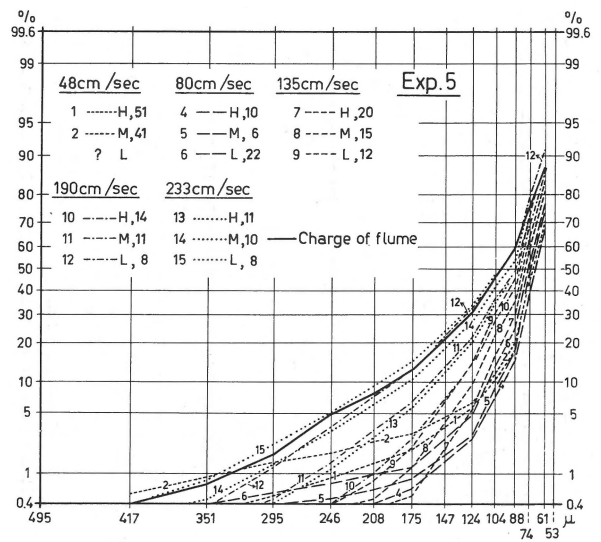
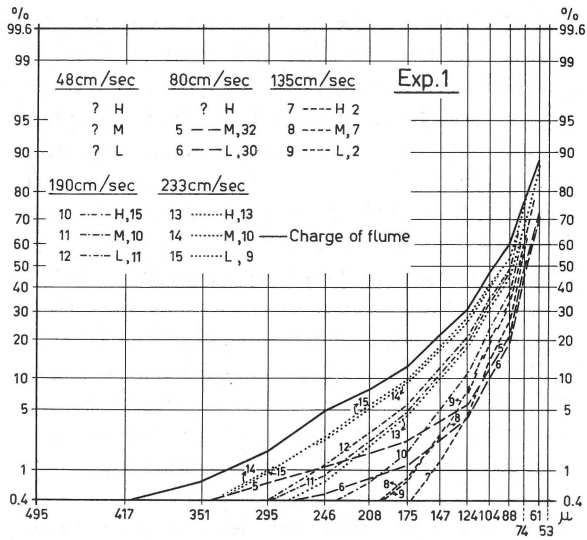
A remarkable result was that with gradual lowering of the velocity a sharp transition took place between 300 and 310 cm/sec to a normal distribution of sand through the cross-section. Sampling for suspension compositions was therefore restricted to velocities of 300 cm/sec or less.

The explanation of this peripheral concentration must be the centrifugal force carrying the sand towards the outer wall. The spiral flow then sweeps it over the bottom up the inner wall and across the surface back to the outer wall (see Fig. 4). Actually it was found that the upper paddle samples contained a slight admixture of sand and presumably a higher concentration would have been found if this siphon had been installed closer to the surface.

Fig. 5 shows the grain size distribution of the various materials used. In Table I the charge of sand and clay introduced into the flume is given. Table II,A and II,B show the velocities for all the experiments and the suspended loads of silt and sand (coarser than 33 microns) in the samples taken by means of the three (later five) siphons.

The grain size distribution of a number of samples was found by ro-tap sieving. For the sandy charge placed in the flume it was calculated from composition and amounts of the commercial sands used. For Exp. 33 the charge was found by analysis of a section from the deposit after total deposition and some desiccation.

¹) In this paper the total mass of sandy sediment (>33 microns) placed in the flume is called the *charge*. The weight of sandy sediment in suspension per litre or the total amount in suspension are called the *load*.



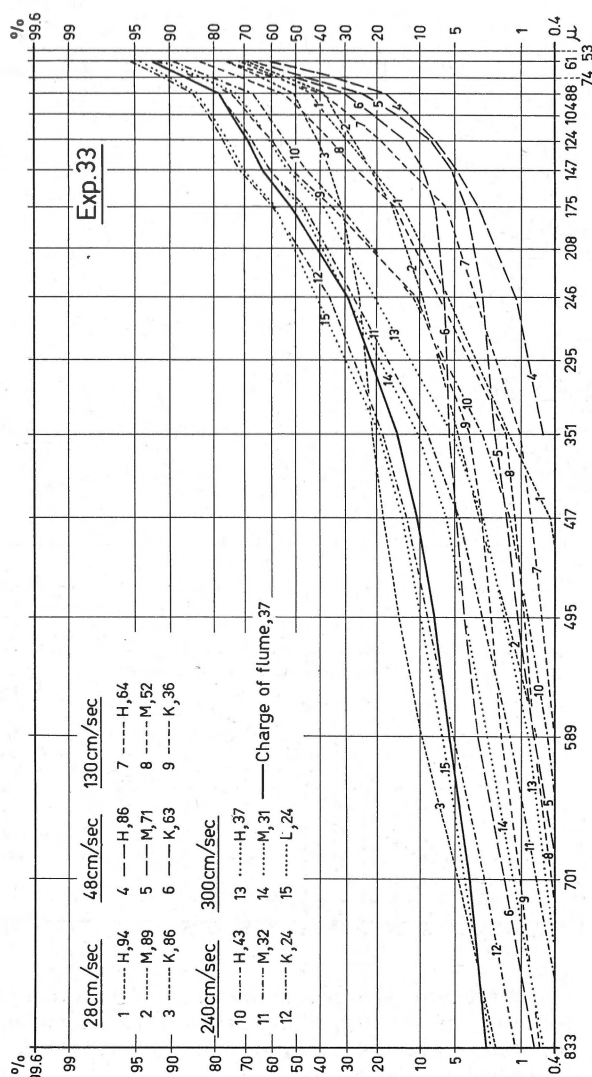
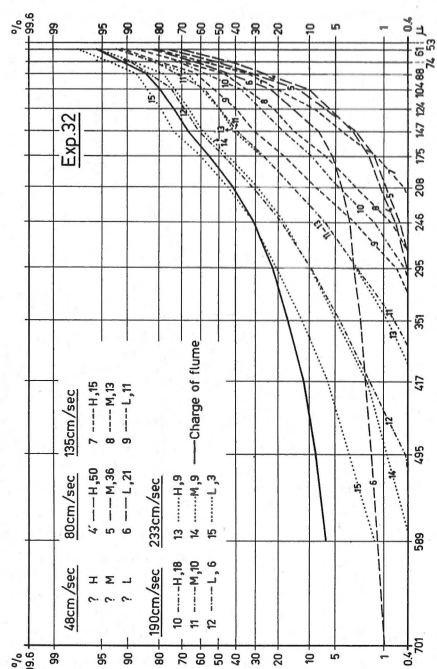
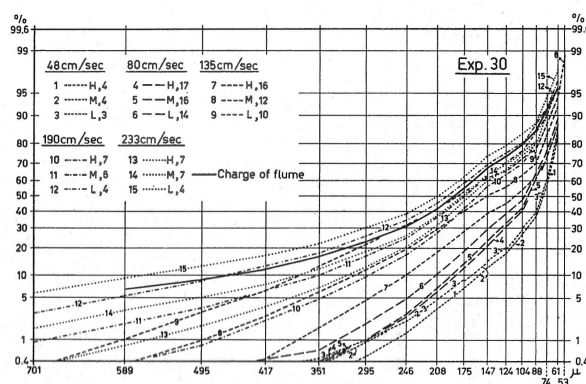
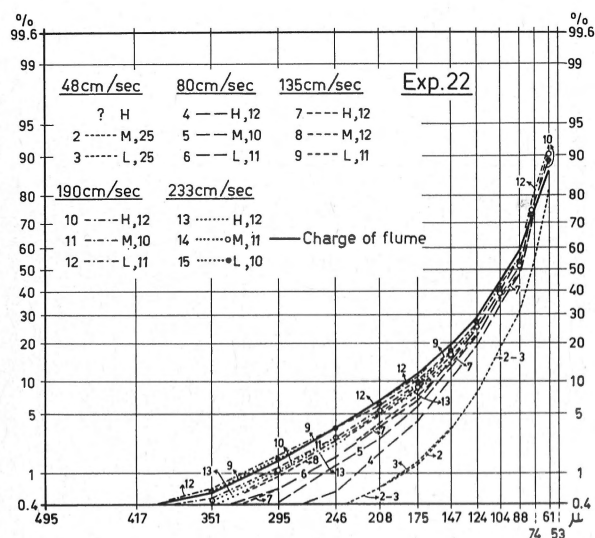


Fig. 6

Eight diagrams with cumulative curves for grain size distribution in arithmetical probability scale, for material coarser than 53 microns. Upper left hand shows amounts between 33 and 53 microns in percentage of whole sample coarser than 33 microns. The tails coarser than about 124 to 175 microns of the curves with low numbers are caused by mica and lignite. For instance the parts of 5 and 6 in Exp. 1, or of 1, 2, 4, 5 and 6 in Exp. 5 above 124 microns. Without these materials these samples would be practically log-normal (see Fig. 9).

TABLE IIB

Load of samples > 33 microns in gr/litre

Experiment Velocity cm/sec	Level	23	24	34	33	Level	Velocity cm/sec
230	H	245	212		376	H	
	M	254	249		426	M	
	L	273	292		463	F	300
190					504	K	
	H	240	175		532	L	
	M	262	249				
135	L	270	300				
	H	200	90		354	H	
	M	227	156		427	M	
100	L	271	210		475	F	270
	H	164	60		499	K	
	M	189	96		549	L	
80	L	233	130				
	H	136	43		361	H	
	M	160	60		422	M	
65	L	187	82		449	F	240
	H	109	30	34	534	K	
	M	119	40	54			
48	L	130	66	76	284	H	
	H	51	22	19	347	M	180
	M	52	23	25	354	F	
38	L	53	30	28	496	K	
	H	6.5	6.6	8.3	208	H	
	M	6.3	8.3	9.5	265	M	130
32	L	5.7	11	10.8	292	F	
	H	3.5	3.1	1.5	398	K	
	M	2.4	2.3	3.7			
	L	3.5	2.3	1.6	139	H	
					206	M	48
					246	K	
					52	H	
					87	M	28
					101	K	

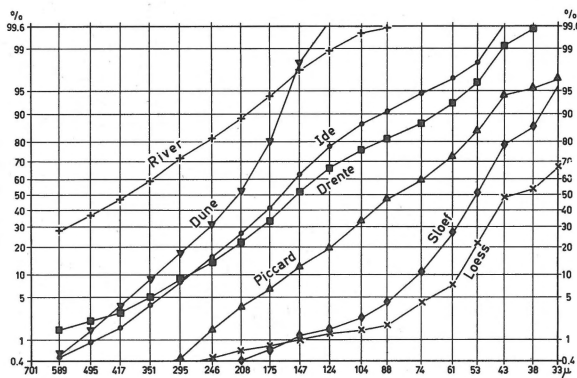


Fig. 5

Cumulative curves for grain size distribution of materials used as charge of the flume. Ide, Drente, and Piccard are peri-glacial sands; sloet is a deposit of the former Zuider Zee. Logarithmic probability scale.

III. RELATION BETWEEN VELOCITY AND GRAIN SIZE OF THE SUSPENSIONS

When treating fluvial transport a distinction is usually made between *competency* and *capacity*. The competency, or maximum grain size transported at a given velocity, has been extensively studied and results were compiled by Hjulström and by Sundborg (1956). Most emphasis has been laid on rolling-competency, but saltation- and suspension-competency are quantitatively at least as important for most situations. For turbidity currents and waning rivers the latter parameter is by far the most significant, but it has been treated very summarily in experimental work.

Capacity, or the maximum amount that is held in

motion has been much less studied. In textbooks it appears that authors apply the concept, as if each size in the spectrum of the load remains uninfluenced by the others. This is manifestly impossible for it would lead to a larger load if narrower sieve fractions were taken into account.

The present investigation has brought out that for suspension transport competency and capacity are interrelated and vary between wide limits according to grain size distribution of the suspended sediment. It is, nevertheless, useful to emphasize the two aspects separately. The combination, involving both grain size and amount will be referred to as "carrying power".

A) Competency

To study competency grain size analyses were carried out on the samples of eight representative experiments. The results for material coarser than 53 microns are shown as cumulative curves on arithmetical probability diagrams in Fig. 6. In addition, the composition of the charge of the flume is also shown. The amounts of medium silt (33-53 microns) will be examined later. They are added in the upper left hand corner of the diagrams.¹⁾

When judging the cumulative curves it should be held in mind that not all velocities are represented in all experiments. This is because in some cases the currents were already loaded to capacity at less than maximum velocity, so that no significant influence can be expected from higher velocities. In other experiments the amounts in suspension at low velocities were too small for making a grain size analysis.

Position of siphons. In some experiments the cumulative curve for the lowest sample taken at maximum current velocity is hardly higher, or in Exp. 1, even lower, than shown by the charge. At higher levels the samples are even finer. As all the sand is in suspension at the highest velocity the coarsest grains must be contained in the suspension somewhere. The most plausible supposition is that the larger grains did not reach the level L where the coarser samples were drawn off. This sample point had to be located 13 cm

off the bottom so as not to be submerged in the deposit at lower velocities.

Coarse tails. Several curves for low-velocity samples show coarse tails (exp. 1: 5, 6; Exp. 5: 1, 2, 5, 6; Exp. 8: 1, 2, 3, 6; Exp. 32: 4, 5, 6; Exp. 33: part of all tails). These tails are due to a small percentage in the charge of the flume of fairly large mica flakes and low-density particles such as lignite and natural pellets cemented by organic matter. In Exp. 33 also some crushed coal and brick were added to bring out lamination. In the experiments without coarse grains they play a significant part for the sieve fractions of low-velocity currents above 124 to 175 microns. The low-density particles remain in suspension near the bottom at low velocities (28 to 80 cm/sec). At higher levels they play a somewhat smaller part. At high velocities much more sand is raised and the light particles are disseminated through the whole body of water. Both circumstances reduce the importance of the particles in the composition of high-velocity samples. By way of example in Exp. 5 lignite predominates above 351 microns in curve 11, 14 and 15; above 295 microns in 12 and 13; above 246 microns in 7, 10; above 208 microns in 8, 9; above 175 microns in 1 and 6; above 124 microns in 2 and 4.

Practically all the particles from the 32 cm/sec currents caught on a 33 micron sieve are of the same low-density material. Hence, no sieve analyses were made except for Exp. 33 rich in quartz silt from loess.

Competency plays a modest role. Geologists, while thinking mainly of rolling, have had faith in the dominant role played by competency in current transportation and deposition and have referred constantly to the diagrams presented by Hjulström and Sundborg. In an earlier paper the senior author has shown (K u e n e n, 1966a) that this picture is open to doubt. In experiments, at a given velocity, laminae can be deposited contrasting in grain size. The diameter of the main element in a coarser lamina can be three times that in the underlying fine one. This occurs not only when the current is decelerated slowly (e.g. 1 cm in 30 sec.), but even when it is held constant and ripples are forming.

It is also widely accepted that the competency-principle applies to suspension and that with falling velocity the competency also decreases. Thereby the coarsest fractions of the load are supposed to be successively abandoned.

¹⁾ Some of the samples are shown in a later section in Fig. 11 on logarithmic probability paper, as proposed by Krumbein, but in these the composition of the samples is given inclusive of the sizes between 53 and 33 microns.

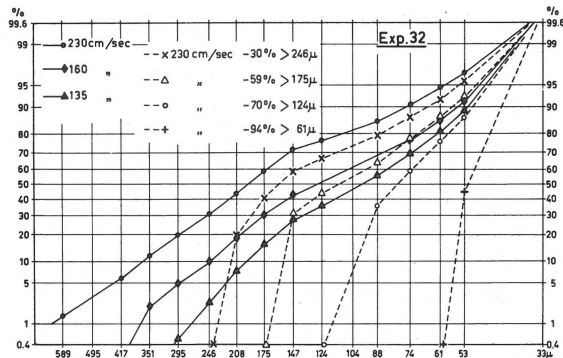


Fig 7

Cumulative curves for grain size distribution (logarithmic probability) of samples taken at L in Exp. 32, shown in full lines, for 230 and 135 cm/sec, the composition at 160 cm/sec is deduced. The loss between the former two was roughly 30%. The dotted lines show the calculated result of subtracting the coarser fractions from L at 230 cm/sec. Losses of 30, 59, 70 and 94%. This represents loss purely by competency.

If suspension competency actually dominated the carrying power then a fast suspension current gradually slackening would drop only coarse sand. The middling and fine grain sizes should not be affected at this stage, for their turn to be deposited would not yet have arrived. The picture would remain the same, but with a gradual shift down through the size range, as the velocity decreased. The result should be a cumulative size curve for the suspension bulging upwards in the central parts. Such a development has been calculated by subtracting coarser fractions from a composition (Exp. 32, 230 cm/sec, L); the result is shown in Fig. 7. It will be seen that development in the flume as the velocity decreases is entirely different from the sequence to be expected from a slackening current dominated by competency as calculated. In a later section this aspect will be re-examined.

When the curves of an experiment are compared with each other and also with that of the charge, a distinct similarity is seen to exist. The general shape and some characteristic irregularities shown by the charge reappear not only at high velocities and at all levels, but are also developed in the low velocity curves, although these represent but a small remaining fraction of the original charge.

Obviously, then, the original composition of the charge is an important factor in determining what

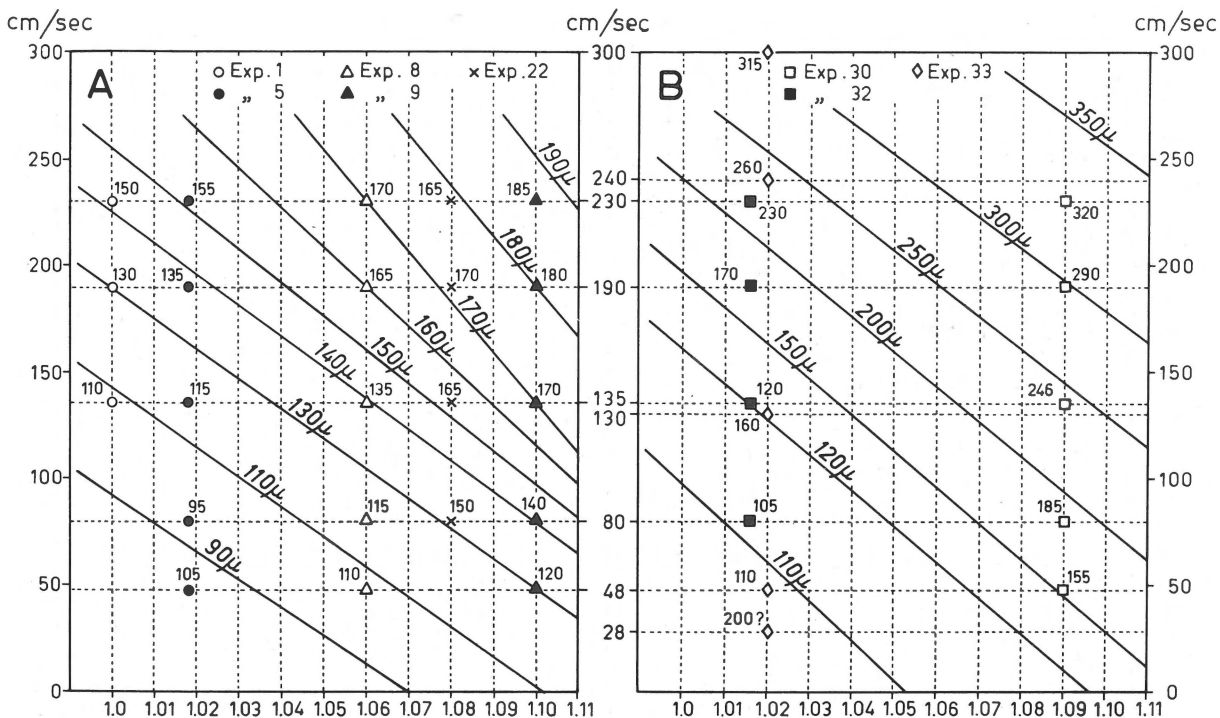
part of the load a waning current discards. No less evident is the conclusion that all grain sizes in the suspension are being lost to the current simultaneously during deposition. It should be taken into account that in many of the tests at higher velocity the largest size in suspension is limited by the maximum grain size available in the charge. For Exp. 27 and 28 and more especially 29 and 33 larger grains were included.

On the other hand the maximum and median grain sizes remaining in suspension in a waning current gradually shift towards the finer end of the spectrum. This means that the larger the size the more, relatively, is dropped from suspension. Hence, competency does exert a certain controlling influence on the loss.

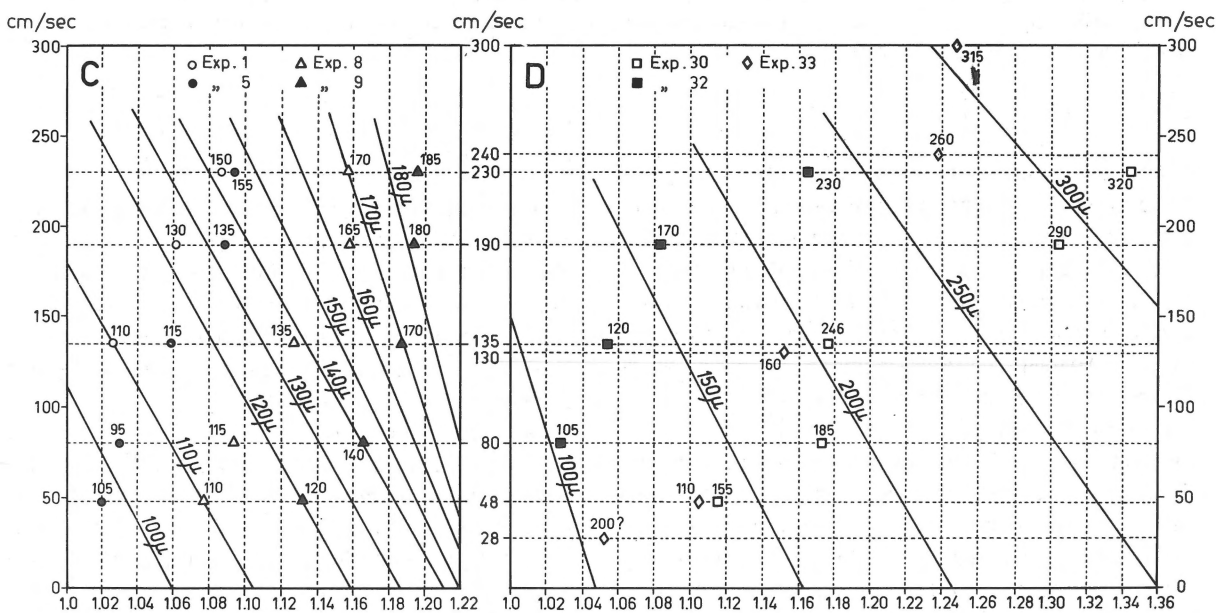
This element of suspension competency is brought out very distinctly in the diagrams of Fig. 8. They show the grain size at 10 per cent on the cumulative size curves as related to velocity and density of the lutum suspension. The data are divided over two diagrams: one for the experiments with fine sand (A) and one for the tests that included also coarse sand (B). Exp. 22 had a suspension density of 1.04 caused by Wadden Sea clay, which is much more active in raising the carrying power than the other types of lutum used. The data of this experiment are shown at double the true suspension density, but velocity has no significant influence on the 10 per cent values of this test so that the fit is very poor.

The "contour-lines" have been spaced more or less regularly. According to this rather exacting test the data are fairly rough, but a 5 to 10 micron adjustment in the values would suffice in all but one case in A to ensure a perfect fit and double that amount is needed in B. Considering the range is from 90 to 190 microns in A and 110 to 350 in B the discrepancies are actually not of real significance.

The size-increase with increasing velocity and with growing density is conspicuous. It is also noteworthy that the values in diagram B increase to almost double the maximum in diagram A because of the availability of coarser material, but presumably also owing to the larger charge which raises the bulk density to higher values. A higher density of the suspension caused by sand should tend to influence competency in the same manner as a higher density of lutum. In other words, when more sand is available the competency should be somewhat raised. This contention is illustrated graphically in Fig. 8, C and D, which are analogous to A and B, except that the density is that



Density lutum suspension



Density lutum + sand suspension

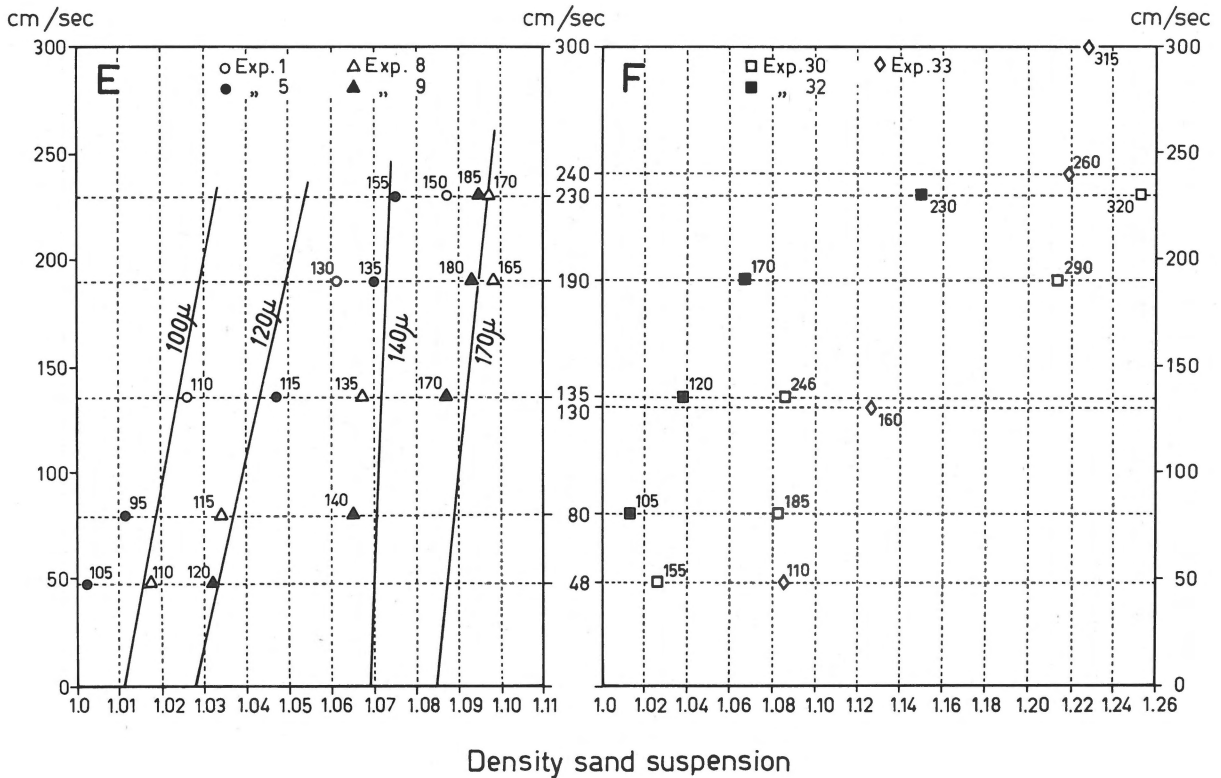


Fig. 8

Diagrams showing lower margin of grain size for coarsest 10% set out against velocity and density of lutum suspension for highest sampling level. A, for experiments with fine sand (Exp. 1, 5, 8, 9); B, with fine to coarse sand (Exp. 30, 32, 33). It is obvious that the competency (carrying power?) of the experiments under A must have been higher than the data show, because the charge was fine grained. The same for total density (lutum + sand) in C and D (note different scale for density). The same for density caused by sand only, E and F. The contours have been drawn straight and spaced regularly because the data are insufficient to warrant a less uniform grid.

caused by lutum plus sand in suspension. A cumulative effect is brought out by the steep lines, namely that with increasing lutum density the capacity for sand is also enlarged and hence the total density.

These diagrams show that over the range of lutum densities from 1.0 to 1.1 the suspension competency for the coarser fractions increases as much as is caused by a velocity increase for the density 1.0 amounting to roughly two metres per second. In diagram A there is an indication that lines become steeper towards the upper right hand corner, a trend that is not shown in B, possibly for lack of data.

It comes as a surprise to find that in a slackening current competency is largely overshadowed by composition of the original charge taken into suspension, combined with a limit to capacity.

B) Capacity

Information on capacity for material larger than 33 microns is provided in this investigation in the first place by the weight of sediment per litre of suspension shown in Tabel II, A and II, B and in the second place by grain-size analyses. For an unsorted load the maximum weight held permanently in suspension could be called "bulk capacity".

An aspect that should be held in mind is that the charge is in many experiments smaller than the capacity at higher velocities. This is evidently the case when higher velocity does not go with greater load. Then the data only demonstrate the capacity for the lower velocity. Examples are seen in Exp. 9 and 10 where the load at 135 cm/sec is already equal to that at 190 and 230 cm/sec.

An important question, on which the experiments give only an ambiguous answer, is whether an originally higher charge of sediment placed in the flume influences the load at lower velocities. Exp. 10 is identical to Exp. 9 except that the charge of sand has been increased. At 135 cm/sec nearly all sediment is still in suspension, but at 80 cm/sec the higher charge causes a higher load. The difference has disappeared at 48 cm/sec. Exp. 11 and 12 have higher charges when related to volume than Exp. 10 and this shows up still at 80 cm/sec where the loads are already dropping, but the comparison is hampered by lowered water content resulting presumably in more turbulence because the paddles dip less deeply into the current. Exp. 27 has a higher charge than Exp. 26 and this causes a higher load at 135 cm/sec where the loads are already decreasing. However, at 80 and 48 cm/sec the higher charge results in a lower load, whereas at 32 cm/sec it is again higher. Exp. 29 shows increase over Exp. 28, but the excess load continues to 48 and even 32 cm/sec (these two experiments have lowered water levels). Exp. 30 compared to Exp. 26, on the other hand, has a higher charge, but the load is less at 135 and at 80 cm/sec, being again equal at 48 cm/sec.

Capacity is found to be by no means a simple concept when applied to suspension of mixed grain sizes. For a narrowly ranging grain size a flume current of given velocity and lutum density has a well defined capacity. But in a suspension with a wide range in grain sizes, such as used in the experiments and occurring normally in turbidity currents, the capacity is not purely an addition of the capacities for the various sizes. On the contrary the measurements show that the capacity at the higher sampling point is not much larger for a wide than for a narrow range of size: at 190 cm/sec Exp. 27 against Exp. 26; or at 230 cm/sec Exp. 30 against Exp. 27 with slightly less clay. This independence of grain size is so marked that the composition of the deposit between two decreasing velocities is largely dominated by the grain size distribution of the suspended load. The remaining suspension at the lower velocity is finer grained with a lower maximum and median size, but sinuosities of the cumulative curve remain much the same. This means that any size over- or under-represented as compared to the amount in a sample giving a fairly straight line on log-probability paper is deposited in much the same relation leaving a suspension in which it is still over- or underrepresent-

ed without significant change.

The data allow some general rules to be formulated.

(1) The load shows an increase from high to low levels. There are arbitrary irregularities and a few exceptions to this rule. The higher the velocity the smaller the difference between the levels. Therefore, when the whole charge is taken into suspension, further increase of velocity will cause a lowering of the load at the bottom.

(2) When a current is loaded to capacity decrease in velocity causes decrease in load. Difference between high and low levels is at a maximum during deposition and is smaller when the current is under-loaded. If under-loaded then velocity decrease causes concentration towards the bottom until capacity there is exceeded, causing deposition to start.

The small amounts held in suspension at 32 cm/sec consist mostly of low-density material or flakes. In other words of quartz or feldspar only fine silt is held in suspension at that velocity. At 38 cm/sec (Exp. 23, 24) about half is low-density particles and mica flakes (see also Table IV and the section headed Turbidite matrix).

(3) The highest concentrations were found when the water level had been lowered (Exp. 12, 25, 28, 29). These high densities were retained down to 190 cm/sec (or even at 135 cm/sec). The values for average charge per litre in Tabel II are somewhat higher, showing that part of the charge in the flume was not raised from the bottom, or at least not to L, Fig. 4, B. With values of 680 gr/litre (Exp. 29) the density of the suspension must have been as high as 1.46.

(4) With increasing load of fine silt and clay the amount of sand held in suspension also increases and the difference between the levels becomes less. This is well demonstrated by Exp. 3 to 9 with lutum densities of 1.003 up to 1.10. The average load increases more than 5 times for the velocity of 48 cm/sec and twice at 135 cm/sec. At 230 cm/sec the difference between upper and lower levels is seen to decrease from 90 gr/litre in Exp. 3 to 5 gr/litre in Exp. 9 as the lutum rises.

To judge in general the influence of lutum on the amount of sand in suspension it should be recalled

that in many experiments the capacity is higher than the charge. It is then seen that the average density at 190 cm/sec or even at 135 cm/sec is still equal to that at 230 cm/sec. Thus in Exp. 9 the load is still at maximum when the velocity has dropped to 135 cm/sec. The lutum gives a density of 1.1 and the load compared to Exp. 3 with only a trace of lutum for 135 cm/sec is 3x, 2x, 1½x at high, middle and low levels and 9½x, 6½x, 3½x at 80 cm/sec, and 12x, 7½x, 4½x at 48 cm/sec. Exp. 27 with a much higher charge and a density of 1.08 is loaded to capacity at 230 cm/sec and compared to Exp. 3 it contains at the same three levels 3x, 2½x, 2x as much. In Exp. 30, density 1.09, with still greater charge the relation is 3½x, 2½x, 2½x and it is 3x, 2½x, 2x at 135 cm/sec, and 12x, 8x, 4½x at 80 cm/sec and 9x, 6½x, 3½x at 48 cm/sec. The higher values at higher levels of middling velocities reflect the more equal distribution over the entire depth with higher lutum contents. With falling velocity the lutum has a relatively even greater influence on the carrying power than in fast currents. The experimentally attained maximum is 12x.

Because depositing turbidity currents are gradually decreasing in velocity it may be assumed that they are always loaded to capacity.

The suggestion is offered that it is the increased viscosity and density of the lutum suspensions that adds to the carrying power, evinced by increase in load and decrease in downward density grading.

In the experiments the difference in load between low- and high-density currents (Exp. 1-9) decreases as the velocity becomes greater. This is mainly due to an experimental condition. At the higher velocities even the clear-water currents were able to raise the entire charge of the flume. Hence, the addition of lutum could not result in a heavier load. This influence of availability is brought out by Exp. 10 with a larger charge than Exp. 9, resulting in greater loads at all velocities above 48 cm/sec. It is possible that an additional effect is in operation and that the differences in viscosity due to lutum become less as the turbulence increases. The action of an opposing factor cannot be excluded. The amount of sand in suspension rises with the velocity and the consequent increase in bulk density may boost the carrying power.

(5) The artificial sea water had no perceptible influence with low contents (Exp. 2 and 3). At higher

clay contents (Exp. 14 and 15, density 1.06) about 17 per cent more fine sand was raised in the sea water at velocity 135 cm/sec and 75 per cent at 48 cm/sec than in fresh water.

(6) Comparison of the effect caused by various kinds of clay shows that the coarsely flocculated Wadden Sea clay had the strongest influence. Exp. 22 with Wadden Sea clay and a suspension density of 1.039 raised twice as much sand at 135 cm/sec, 4 times as much at 80 cm/sec, and 3 times as much at 48 cm/sec as the slightly more concentrated suspension of china clay in Exp. 7. The charge was higher in Exp. 20 (Wadden Sea clay) than in Exp. 5 (china clay), the suspension density smaller, but at 135, 80 and 48 cm/sec almost twice as much sediment was raised. The additions of bentonite or Brunssum pottery clay up to more than half the china clay had no appreciable effect (Exp. 15 to 19). The conclusion is warranted that in nature the type of clay had no great influence. But owing to more pronounced flocculation natural lutum would tend to play a more significant part than would be deduced from the experiments with commercial clays.

(7) In Fig. 9 the suspensions are divided into 6 groups according to density of lutum suspension above that of clear sea water, with one separate group for lowered water surface (more turbulence). For each density the relation is shown between velocity and grams per litre of sand (coarser than 33 microns) at the high sampling point (= H).

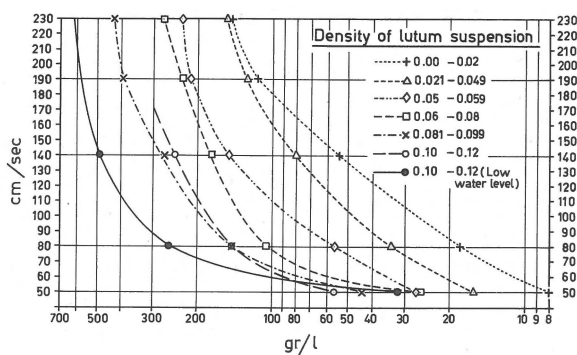


Fig. 9

Relation between velocity and grams per litre coarser than 33 microns at capacity for highest sampling point (= H) for various ranges of density as caused by the lutum.

The experiments with Wadden Sea lutum, loess and some of the tests with added coarse sand and likewise cases where the current was not loaded to capacity have been left out of account.

It is obvious that the curves tend to approach asymptotically to a maximum between 200 gr/l for the low densities and 500 gr/l for the high densities in both cases estimated at about 4 m/sec. Possibly these values represent the maximum load that will flow fully turbulently? At the other end the load becomes zero as far as quartz sand is concerned at about 30 to 40 cm/sec, because the small amounts at low velocities are low-density particles.

The highest average load measured was in Exp. 29 for velocities upwards of 1.5 m/sec. The value obtained of 680 gr/l does not grow at 230 cm/sec and is lower than the average deduced from the charge, namely 790 gr/l. This indicates that the samples may not have been taken at points of maximum concentration. It will be assumed that the load at 1.5 m/sec averaged 725 gr/l, giving a suspension density for all solid matter of 1.53. The suspension was highly mobile showing no tendency to slide but only for turbulent flow. If experiments with lower water level are ignored, the highest sand load at the upper level was 440 gr/l (Exp. 30) in a lutum suspension of density 1.09, hence with a total density of 1.35 at a velocity of 233 cm/sec. When only fine sand was available to the current the maximum sand load in a lutum suspension of density 1.1 was 305 gr/l (Exp. 11) at 1.5 m/sec, giving a total density of 1.27.

Presumably higher densities than observed can occur at higher velocities. This confirms the deduction made from earlier experiments that superficial sea floor sediments contain sufficient water to be capable of high-velocity turbulent flow after being sufficiently disturbed. However, in estimating the load of natural currents, densities of 1.5 are the highest that can be legitimately postulated and only for high velocities (several metres per second) and for the most concentrated parts of the whole body.

Until more is known concerning turbulence, velocity and lutum density at various levels in a natural turbidity current it is hardly possible to estimate capacities. But the experimental data suggest that at densities around 1.01 due to lutum in the lower parts of the current the sand load will not be much more than it would be in a similar flow of clear water, but that at high lutum densities, around 1.1 the load held in suspension could be 2 or 3 times as high for

velocities upwards of 3 m/sec, and up to 5 times as high for velocities of $\frac{1}{2}$ to $1\frac{1}{2}$ m/sec. These ratios are suggested for currents loaded to capacity. This condition of full loading should hold for all turbidity currents, but less commonly for rivers because the former are always decelerating. Moreover, only rivers in spate in arid climates show such high lutum values. In normal rivers there is comparatively little clay available during peak stages of flow. In a former paper evidence was presented (Kuenen, 1966b) that natural turbidity currents tend to show lutum densities of 1.03 to 1.07. The part played by decreasing capacity of a slackening suspension current in producing a deposit will be treated in the section on deposition.

The higher concentration in the tests with lower water level (Fig. 8) are evidently due to increased turbulence resulting from more slip of the paddles. It follows that all present experimental values are higher than they would be in a current driven by gravity on a slope. On the other hand the smooth surface presumably leads to less turbulence than would occur if there were a covering stratum with gradual upward decrease in velocity. The spiral flow in the flume may also tend to boost the carrying power. When applying the data to natural currents it appears advisable to suppose a higher velocity, to correspond with compositions similar to those of the experimental suspensions.

C) *Interrelation competency-capacity*

The interrelation of capacity and competency can be further demonstrated by calculation of the amounts in suspension per litre for each grain size and for different velocities (A for the highest velocities and B, C, D for the slackening currents). Then the ratios of these amounts are deduced at successively decreasing velocities, hence A/B, B/C etc. These ratios are plotted against the grain sizes (on log normal paper) in Fig. 10. Complicated but systematic relations are found. This shows that the ratios, that is the change in capacity with slackening current, differ not only for each successive change in velocity, but also for each grain size, the latter being a matter of competency. Obviously, therefore, competency and capacity are interdependent.

Two cases are illustrated; Exp. 5 had a modest amount of fine sand in a medium dense suspension of china clay, whereas Exp. 32 had a large charge of

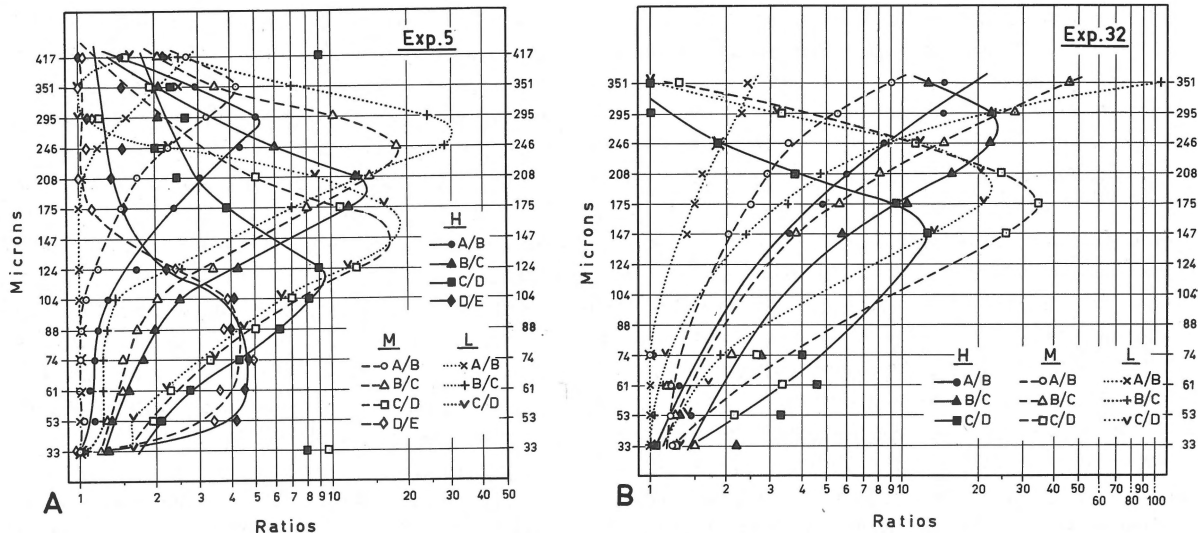


Fig. 10

Ratio between grams per litre in the various sieve fractions at two velocities (A/B; B/C; C/D; D/E for A = 230, B = 190, C = 135, D = 80 and E = 48 cm/sec). The diagrams show the variation with grain size at three sampling levels (H = high, M = middle, L = low, see Fig. 3). Exp. 5 and Exp. 32. Without low-density grains and mica flakes the curves would bend back more sharply towards the larger grain sizes.

poorly sorted sand in a low density suspension of mixed clays. Exp. 30 had the same charge as 32 but possessed a much higher clay density. As it showed the same relations, the calculated ratios are not illustrated.

The diagrams show that the ratios are in general highest for the largest grains and for the highest level. It is also highest for the lowest current velocity assuming that the difference in velocity between A and B is roughly proportional to that between B and C, etc. However, the ratio shows a decrease above a certain grain size. This feature occurs at smaller grain sizes for the higher levels and lower velocities.

The explanation of the various trends appears to be as follows. The further suspension competency is above a certain grain size, the less the capacity sinks with decrease in velocity (low ratio). The upward decrease in competency therefore results in higher ratios (L → M → H).

Conversely, the closer a grain size approaches suspension competency the more it will be affected by further drop in velocity. Each successive drop of equivalent magnitude will have a greater effect because of closer approach to competency. Hence $A/B < B/C < C/D < D/E$.

A number of ratios are below unity. This would mean an increase in capacity with falling velocity, but it is probably attributable to vortices and inaccuracies in both sampling and in methods of analysis. The repeatability of sieve analyses and the equality of splits cannot attain high accuracies.

The bend back to low values above a certain grain size shown by most curves results from the interplay of two factors. Part of the sand and clay used contained some lignite particles of low density and mica flakes, as explained above. In cases where capacity was low these particles remained in suspension and played an important part in determining the grain size distribution, because the load of coarser quartz grains became small or even disappeared. Being still far below suspension competency the ratio for this coarse material was low. Apart from the minor admixture of mica we are dealing with an unnatural aspect of the experiments. Inspection of the sieve fractions shows that the bends tend to occur at the smallest grain size that is dominantly lignite in the lower velocity sample of the couple compared.

However, the curves must bend back to one beyond a certain maximum, because for all grain sizes well above competency the ratios are unity. Com-

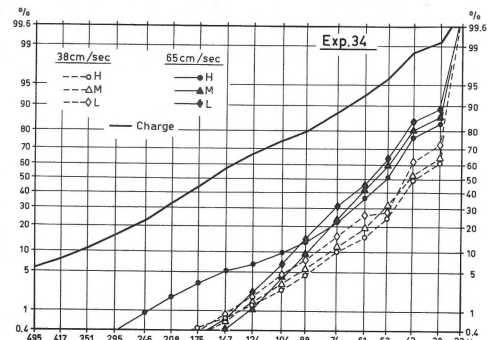
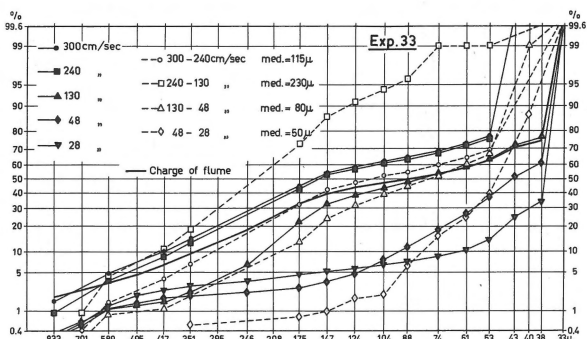
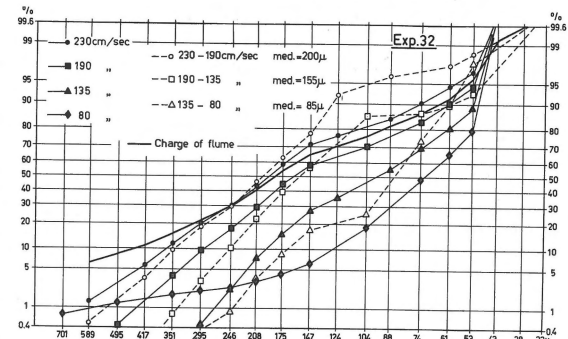
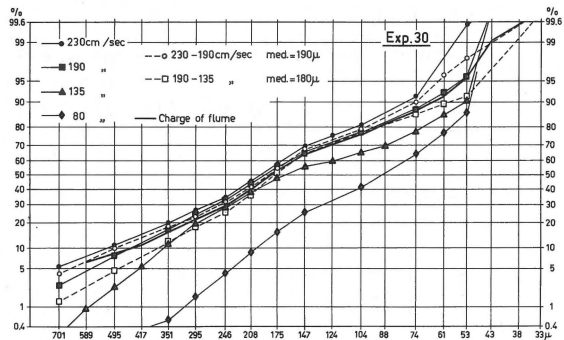
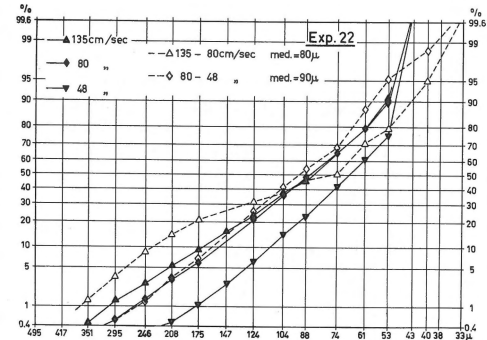
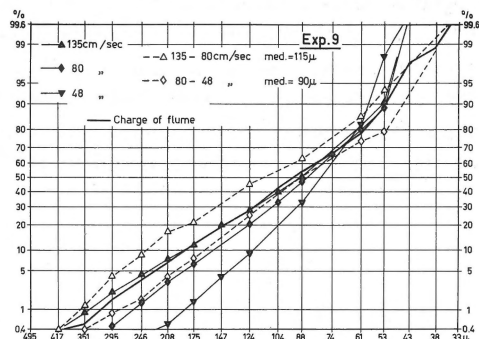
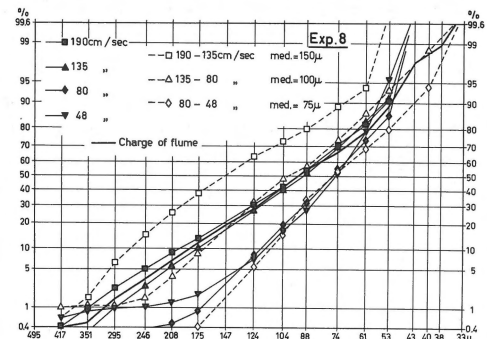
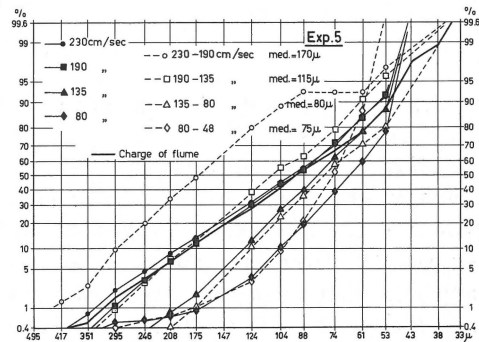
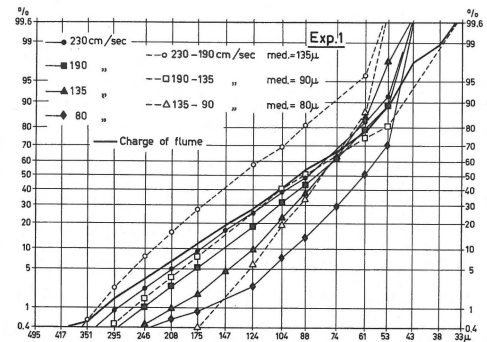


Fig. 11

Nine diagrams with cumulative curves for grain size distribution on logarithmic probability scale for material coarser than 33 microns. Samples taken close to the bottom (L) at various velocities. Dotted lines represent calculated composition of deposits formed between two decreasing velocities. All curves are practically log-normal except for the coarse tails of the finer samples (= lignite and mica) and for the lutum tails of these washed samples. The deposit of the experiments with a fine-grained charge (Exp. 1, 5, 9, 22) are in general coarser than the suspension sample at the higher of the two velocities concerned. The last formed deposit, however, (below 190 or 135 cm/sec) is finer. In the coarse-grained experiments (30, 32, 33) most deposits are finer than the suspension at the higher of the two velocities concerned.

petency is not a sharply defined grain size, otherwise the grain size distribution in the suspension would be cut off abruptly on the coarse side. The percentage of lignite in the charge becomes less with increasing grain size. The fact that the backward bend becomes sharper the larger the grain sizes are at which it occurs, presumably means that in pure quartz sands the bend would occur at the same grain size as in the diagrams but would be even more pronounced. It is tentatively suggested that the grain size at the bend is the best measure to give an upper limit for suspension-competency in the experiments. In the experiments the maximum grain diameter is roughly double this size, but without lignite it would be less.

IV. MEDIAN GRAIN SIZE OF SUSPENSIONS

The fact that the experiments demonstrate the close link between composition of load and charge of flume, has its reverse in their unsuitability to show the link between velocity and maximum grain size. In other words, the median (> 33 microns) of the suspensions at a given velocity which show a wide range according to the composition of the sand charge, are only slightly influenced by the lutum density.

Thus, at velocity 230 cm/sec the median varies between 80 and 100 microns for all densities and sampling levels in the experiments with fine sand

TABLE III

Grams of medium silt (33-53 microns) per litre of suspension

Exp.		28 cm/sec	48 cm/sec	80 cm/sec	135 cm/sec	190 cm/sec	230 cm/sec	300 cm/sec
1	H			—	0.9	15.2	18.3	
	M			5.6	5.3	14.4	16.8	
	L			10.8	2.2	21.8	20.4	
5	H		3.6	1.6	12.6	15.8	15.4	
	M		4.5	1.5	13.5	17.2	17.0	
	L		—	10.1	16.4	17.0	16.3	
8	H		2.2	12.1	15.4	15.1	15.9	
	M		1.7	12.5	15.4	15.1	16.9	
	L		1.3	16.1	14.3	15.2	16.9	
9	H		1.1	1.1	16.8	17.6	18.2	
	M		1.1	15.4	15.9	16.4	15.8	
	L		1.2	15.5	16.2	15.8	15.3	
22	H		—	22.4	26.6	29.5	29.2	
	M		13.1	20.9	29.2	25.4	26.3	
	L		16.0	24.2	27.4	28.8	25.1	
30	H		1.7		23.5	27.2	30.7	
	M		1.8		22.7	28.4	35.4	
	L		1.4		25.3	22.0	23.3	
32	H			10.5	11.1	23.0	22.1	
	M			12.2	14.6	21.9	36.5	
	L			16.4	21.3	23.2	17.2	
33	H	48.9	119.5		133.1		155.8	139.1
	M	77.4	146.3		137.8		135.0	132.1
	L	86.9	155.0		143.3		128.2	121.0

charge. But with coarse sand added the range is from 115 and 205 microns. Table II and Fig. 11 show both how the medians decrease with velocity and also the influence of the charge on the capacity. At 48 cm/sec the latter influence has practically disappeared. The calculated medians of the deposits formed between the two velocities are added in Fig. 11. These are coarser than the suspension, otherwise there would be no shift towards finer grain as the velocity decreases (influence of competency).

V. MEDIUM SILT

The amounts of medium silt (33-53 microns) in suspension (as grams per litre) can be calculated from the percentages and the total loads. These values are found to be somewhat irregularly distributed (Table III). Presumably this is caused by inaccuracies of the methods of analysis and possibly the distribution was not as simple as might be supposed.

The amounts tend to be equally high for velocities of 230 and 190 cm/sec (Exp. 5, 30, 32) and in some cases also 135 cm/sec (Exp. 8, 9, 22, 33); but for one case (Exp. 1), poor in clay, the amounts are already less for 190 cm/sec. At 48 cm/sec the values have dropped to the following fractions Exp. 5 = 0.24; Exp. 8 = 0.11; Exp. 9 = 0.07; Exp. 22 = 0.35; Exp. 30 = 0.06; Exp. 33 (28 cm/sec) = 0.51.

In the majority of tests the amounts at high velocities decrease from the highest to the lowest level. This is presumably in part a result of downward increase in sand, leaving less volume for silt, that is uniformly mixed in the turbulent water. At lower velocities, on the other hand, the silt content increases downward with few exceptions. This is evidently caused by insufficient turbulence to mix the medium silt uniformly through the flow. This is already the case for the velocities that fall just short of carrying the maximum load. In other words in all eight experiments the maximum load persists at the lowest sampling point when the turbulence is just insufficient to raise the medium silt right up to the surface.

A small part of the decrease in silt with drop in velocity can be attributed to entrapment of more than average in the deposits already formed.

A tentative conclusion with relation to turbidity currents is that when the lower part is travelling at 80 cm/sec it will gradually be losing much of its

medium silt. However, if a thick sheet of flowing water is dropping large quantities of silt into the layer close to the bottom already containing e.g. 150 gr per litre, then deposition will be postponed till the velocity has further decreased.

VI. TURBIDITE MATRIX

The distribution of silt throws light on the matrix of turbidites. Theoretically the term matrix should only be used in cases where there is a size-gap between the coarser grains of a sediment and the finer filling. However, for practical reasons about 30 to 35 microns in a continuous spectrum of sizes is a useful demarcation because this is about the smallest size that can be conveniently studied under the microscope and treated by sieving.

In the present investigation all particles of suspension samples finer than 33 microns were washed away. In other words the matrix-forming material was discarded and the silt to sand sizes retained for sieving analysis. For several reasons the cumulative curves shown in Fig. 6 were restricted to the sizes coarser than 53 microns, but the amount of silt (33-53 microns) for the entire washed sample has been noted separately in per cent. Some cumulative curves were also plotted on log-probability paper for all sizes coarser than 33 microns (Fig. 11).

In an earlier paper the senior author (K u e n e n, 1966b) sought to account for the lutum (= smaller than 33 microns) in turbidites by entrapment of the suspension in the pore space of the sandy deposits. The lutum content of the currents was determined from samples scooped out at the surface. The supposition was shown to hold for experimental conditions down to median grain sizes of 300 microns. With finer deposits, formed at lower velocities, the entrapped amount of lutum was found to exceed the quantity to be expected from the working hypothesis. This was tentatively ascribed to two factors: (1) the development of a traction carpet with a higher lutum content than the remainder of the current (the suspension samples should in that case have been taken closer to the bottom) and (2) compaction after deposition and entrapment (K u e n e n, 1966b, p. 283). Compaction would lower the porosity and extrude water but fail to flush out the lutum caught between the larger grains.

To test the downward concentration of fine

TABLE IV

Grain size of suspended load at 4 levels in per cent.
Density salt-water clay suspension 1.04. Velocity 48 cm/sec.

Grain size microns	L	F	M	H
246	1.7	0.04	0.02	0.02
208	0.3	0.03	0.01	0.02
175	0.3	0.06	0.02	0.01
147	0.5	0.2	0.04	0.03
124	0.8	0.5	0.1	0.04
104	1.7	1.4	0.4	0.1
88	2.0	1.9	0.6	0.3
74	4.1	4.5	1.9	1.1
61	4.6	5.4	2.7	1.7
53	4.5	4.9	3.0	2.7
43	4.5	5.5	4.4	3.4
38	1.5	1.6	1.7	1.3
25	7.3	10.0	9.0	13.2
16	4.1	5.6	11.7	5.6
<16	62.2	58.2	64.1	70.4
gr/l				
>33	32.3	30.8	16.8	11.8

material at low velocities a separate experiment has now been carried out. A salt-water suspension of clay with a density of 1.04 was used with a charge of 350 kg of mixed sand. Samples were taken from points H, M, F, L, (Fig. 4) at current velocity of 48 cm/sec. Table IV presents the analyses inclusive of the finer fractions. It will be seen that for sizes of 88 microns and larger there is a regular decrease from L to H; for 74, 61 and 53 microns the percentages at L and F are about equal, but M and H have lower percentages (and absolute amounts); whereas below 38 microns there is no concentration downwards, if anything the opposite.

At 80 cm/sec the median of the deposit according to the former measurements is about 80 microns and the amount below 33 microns should already be half a dozen times more than would follow from entrapment only. The present data indicate that as there is no downward concentration of particles smaller than 33 microns even in a slower current, this element cannot play a part in producing the matrix of turbidites. Entrapment and active deposition, somewhat supported by compaction, evidently form the principal mechanisms producing this matrix.

In the former paper cited it was supposed that matrix caught between the grains of a coarse deposit produces a steep upward tail to the cumulative size

curve, divided from the main part by a gap in grain size. Although the data in the present experiments are not very suitable for testing this suggestion, some support is forthcoming from the coarsest deposits found by calculation in Exp. 5, 32, and 33, (Fig. 11).

The question can be raised whether fine material can have infiltrated into the pore space of the experimental or natural turbidites in the manner suggested a.o. by Sengupta (1967) for certain fluvial deposits. This possibility can be excluded for turbidites on several grounds. Firstly the coarsest deposits, having the greatest permeability should show the maximum infiltration. Actually the percentage of matrix increases with falling grain size. Secondly there is no bimodality in the grain size distribution to indicate two differently emplaced populations. Thirdly the uninterrupted accumulation must cover and thus protect each increment against infiltration. Fourthly the deep more or less stagnant environment will result in immobile pore water, precluding ground water flow and this must effectively guard against infiltration of lutum.

VII. SEGREGATION IN THE SUSPENSIONS

It was pointed out above that the total amount of particles larger than 33 microns per litre of suspension decreases from the floor upwards. In general this also holds for median grain sizes as can be seen from Fig. 6 or Fig. 11. But it also appears that the finer material is evenly distributed (= total suspension) and the higher the velocity the larger the sizes for which this holds.

To obtain numerical data a calculation was made first of the ratio between weight of sand, at the two levels M and H compared to the amount in the lowest sample (L). Applying these values to the sieve analyses for the sizes larger than 53 microns and smaller than 175 microns the ratio can then be deduced between the amount of a given grain size at levels M and H compared to that at L. Less than unity means more material at the higher levels and more than unity means segregation downwards.

The following rules and numerical data were ascertained.

- (1) The ratio increases upwards. Thus the average of all sizes at M is 1.31 (Exp. 22 : 0.99 to Exp. 32 : 1.72) and at H it is 1.83 (Exp. 30 : 1.04 to Exp. 32 : 3.18).

(2) The ratio decreases with density of the suspension. The experiments can be arranged according to increasing values of the ratio. For sampling point M and H separately the following series are obtained:

for M: Exp. 22-30-9-33-8-34-15-32

for H: Exp. 30-9-22-33-8-15-34-32

density: Exp. 9-30-8-22-33-15-32-34

The sequence is added arranged according to decreasing density of the clay suspensions. Although there are irregularities it becomes evident that the suspension density is the main factor determining the size of the ratio, for high densities result in small decreases upwards.

(3) The ratio increases with grain size. The average for all tests are:

53 microns	1.20
61 microns	1.58
74 microns	1.48
88 microns	1.50
104 microns	1.87
124 microns	1.77
147 microns	2.52

(4) The ratio increases with velocity decrease:

230 cm/sec	190 cm/sec	135 cm/sec	80 cm/sec
1.11	1.28	1.66	2.13

Table IV shows that at 48 cm/sec there is total suspension for particles of 38 microns and smaller in a suspension with clay density of 1.04. For the sizes larger than 43 microns the sizes for which the ratio is below 1.01 are recorded in Fig. 12, A with relation to velocity and density of suspension. At each velocity/density point the sizes are placed, of which the upper figure relates to point H, the lower to point M. The resulting picture is rather irregular, but roughly the near-unity values are found up to larger grain sizes at M than at H. There is also a tendency, especially at higher velocities, for the sizes to increase with higher lutum densities. As generalized result it is found that coarse silt can be totally suspended in a suspension of density 1.05 at about 1 m/sec. and fine sand at 2 m/sec. At 2.5 m/sec and high clay density 124 microns grains can be totally suspended. In low density suspensions at 230 cm/sec no sand is totally suspended only medium silt.

The ratios can be plotted against the grain size for

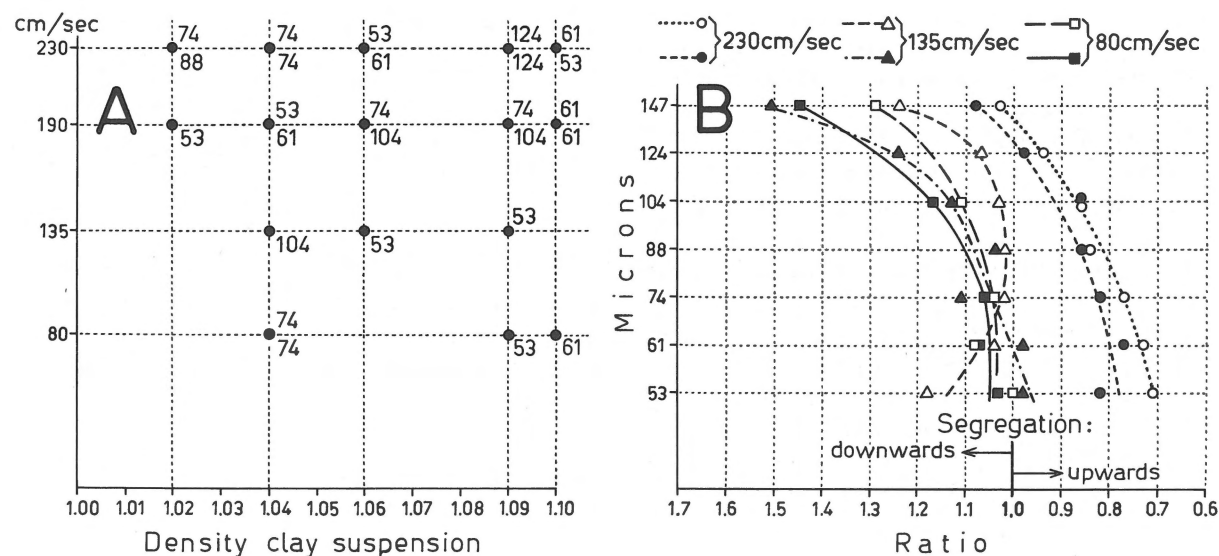


Fig. 12

Ratios between amounts per unit of volume for smaller grain sizes at levels H and M compared to the amount at L (less than unity means upward concentration). A, largest grain sizes for which upward concentration is found at various velocities and for various clay densities. Where smallest size (61-53 microns) shows segregation downwards no values are recorded. At each point the upper value refers to level H, the second one to level M. B, Exp. 30 (density 1.09); values for three velocities, showing fairly regular distribution with marked upward concentrations for highest velocity.

a given velocity, separately for each experiment. An example is given in Fig. 12, B. The smoothed curves are found to cross the unity line down to values of 0.8 or even less for 53 microns, especially at high velocities. This means an upward concentration. This can be accounted for partly by experimental errors and partly by the smaller space occupied by large grains. But the upward concentration is so regularly developed and so large and it increases so smoothly with falling grain size that it is almost certainly real.

VIII. RELATION BETWEEN VELOCITY AND GRAIN SIZE OF DEPOSIT

Two sets of data are available which can be combined to calculate the size frequency distribution for the deposits formed during a certain drop in velocity. On the one hand the amounts of suspended sand and silt (coarser than 33 microns) were measured and on the other hand sieve analyses of several samples at five velocities were carried out. It will be assumed in the first place that the average of the suspension load for the three sampling points gives a reasonable measure for the whole current, and in the second place that the grain size of the sample taken at the middle sampling point is representative for the whole current. This is justified because the average of the highest plus lowest sampling levels comes very close to the value for the middle level. From these two sets of data grain size distribution of the loss between two successively lower velocities can be calculated. The results are shown as cumulative curves in Fig. 11¹⁾

The reader may wonder why no size analyses were made directly on deposits formed over a certain drop in current velocity. The reason is that any sampler placed on the bottom influences the flow and therefore does not take a representative sample. In a former investigation a ripple-shaped sampler was used that functioned adequately for the purpose of finding porosity and matrix (K u e n e n, 1966b). But the

present need is for samples that must be highly reliable for all grain sizes. That is why an indirect method had to be followed.

However, for an investigation concerning ripple mark, the results of which will be published separately (K u e n e n and H u m b e r t, in press) analyses were made of a few rippled deposits formed at measured velocities. After ripple formation the current was stopped and the remaining suspension was drawn off immediately. The deposit was then dried out for sampling. This procedure is much too time consuming, however, for general application. The few data thus procured indicate that the calculated medians are roughly in agreement with analysed deposits (see Table V).

In almost all cases the grain size of the deposits is seen to decrease with the slackening of the current. In other words the tests provide a quantitative counterpart to the grading observed in the deposits of a slackening current. But there is one noteworthy exception. In Exp. 33 the calculated average for the deposit is finer for the velocity drop from 300 to 240 cm/sec than for the drop from 240 to 130 cm/sec. The cause is uncertain, but possibly the abnormally high percentage of medium silt (loess) present in the charge is responsible. The composition of the small amount deposited between 300 and 240 cm/sec is singularly close to that of the charge

TABLE V

Range in median grain size in microns ($> 33 \mu$) calculated for deposits, and measured for suspensions at all three sampling levels, related to current velocity.

Velocity cm/sec	Charge of flume			
	Fine sand = 90μ		Coarse sand = 175μ	
	Suspension*	Deposit	Suspension*)	Deposit
230	80 – 100	135 – 170	115 – 205	190 – 200
190	75 – 95	90 – 150	105 – 180	155 – 180
135	70 – 95	80 – 115	90 – 160	95
80	55 – 90	75 – 90	50 – 95	—
48	50 – 80	—	75 – 80	50
28	—	—	35	—
60	—	—	—	80*
50	—	—	60	90*

* measured

¹⁾ In one case (Exp. 30) the calculated amounts of the finer grain sizes were larger at 80 cm/sec than at 135 cm/sec, which is manifestly impossible in the absence of erosion. As the suspended load at the lower velocity was also relatively large some error evidently occurred in the sampling and hence no composition for the deposit between the two velocities can be given.

with almost identical sinuosity, whereas the curve for the next loss is conspicuously straight. Perhaps loss of capacity for the fines predominated, leaving the relatively small amounts of coarser grains in suspension at the beginning of the deposition.

The cumulative curves for the calculated deposits are strikingly similar in shape to those for the suspensions. The plot on logarithmic probability paper approaches a fairly straight line for both, except in the first place for Exp. 30, 32 and 33 where the charge has a slight nick at 147 microns, traceable also in the coarser samples, and in the second place for an upward bend in most samples occurring below 61 microns.

The bend towards coarser grains in some of the deposits formed at low velocity is again due to the presence of light particles that bulk noticeably in the small amounts held in suspension when the current has dropped below 80 cm/sec. But where slight sinuosity in the line for the charge can be observed it tends to be represented in the lines for the deposits also. A clear example is shown in Fig. 11, Exp. 33, where the same sinuosity appears in the cumulative curves for the suspension at 130 cm/sec and the deposit lost between 130 and 48 cm/sec. It is curious that the finer samples appear to diverge somewhat more from straight lines than the coarser ones. The straight lines at high velocities occur even when the cumulative line for the charge of the flume is distinctly curved (Exp. 33). It is also remarkable that the finer suspensions remaining after a large percentage has been deposited, should show as close an approach to the shape of the charge.

The straight line plot on logarithmic probability paper shown by the deposits indicates that the size frequency distribution is log-normal. Log-normal distribution of grain size is not uncommon in natural sediments, but the mechanism of its development is not fully understood. The junior author is investigating this problem with the assistance of J.S. Rao of the Indian Statistical Institute, Calcutta. It is suggested by them that: "when a certain critical velocity is exceeded, capacity starts influencing competency (and vice versa) with the result that populations of lognormally distributed sizes are continuously lifted up with progressive increase of velocity. This happens even when grain sizes of "the charge" do not have lognormality. It is well known that the product of several independent random variables will tend to be lognormally distributed. In the present case each unit

increase of velocity seems to have a multiplicative effect on the size distribution so that after a critical velocity is reached, the distribution of particle size in suspension approaches lognormality. Conversely, with gradual decrease of velocity, only lognormally distributed size-ranges are deposited by the current."

When fluviatile samples are analysed the sorting according to grain size is found to be much less marked than would follow from the application of the principle of competency as expressed in the diagrams of Sundborg and others. The wide spread in grain size is usually attributed to two main causes: (1) sampling of horizons that are too thick, thus including materials deposited at diverging velocities, (2) entrapment of finer grains between the coarser ones.

The first element of this explanation cannot be applied to the present experiments, because the suspension samples were taken after a period of constant conditions, including current velocity. As a result the deposits represent a narrow range in velocity that would only account for a drop in grain size of the order of one half. If the entrapment is taken as the main cause, the largest grains should form a packing taking up 60 per cent of the volume. The second generation, caught in the interstices, would have about half the diameter and only 8 per cent of the volume. There should result a cumulative curve starting abruptly with 60% and rising very gradually towards the fine end. The actual shape bears no resemblance to this deduced curve. Even when combined, these two elements are entirely inadequate to explain the grain size of the present deposits. Competency certainly plays a part, because the deposits are equal to or coarser than the suspension load near the bottom at the fast end of the velocity interval involved. Moreover, as the velocity decreases the maximum and median grain sizes of the deposit gradually diminish. Suspension competency is also involved because it helps to determine which grain sizes are supplied from higher up-current to the point in question. But competency can be only a contributing factor and it must be that some form of capacity plays a much more important role in determining the composition of the deposit than competency.

Some rules can be formulated for a slackening suspension current:

(1) Capacity is an integrated bulk property. Depen-

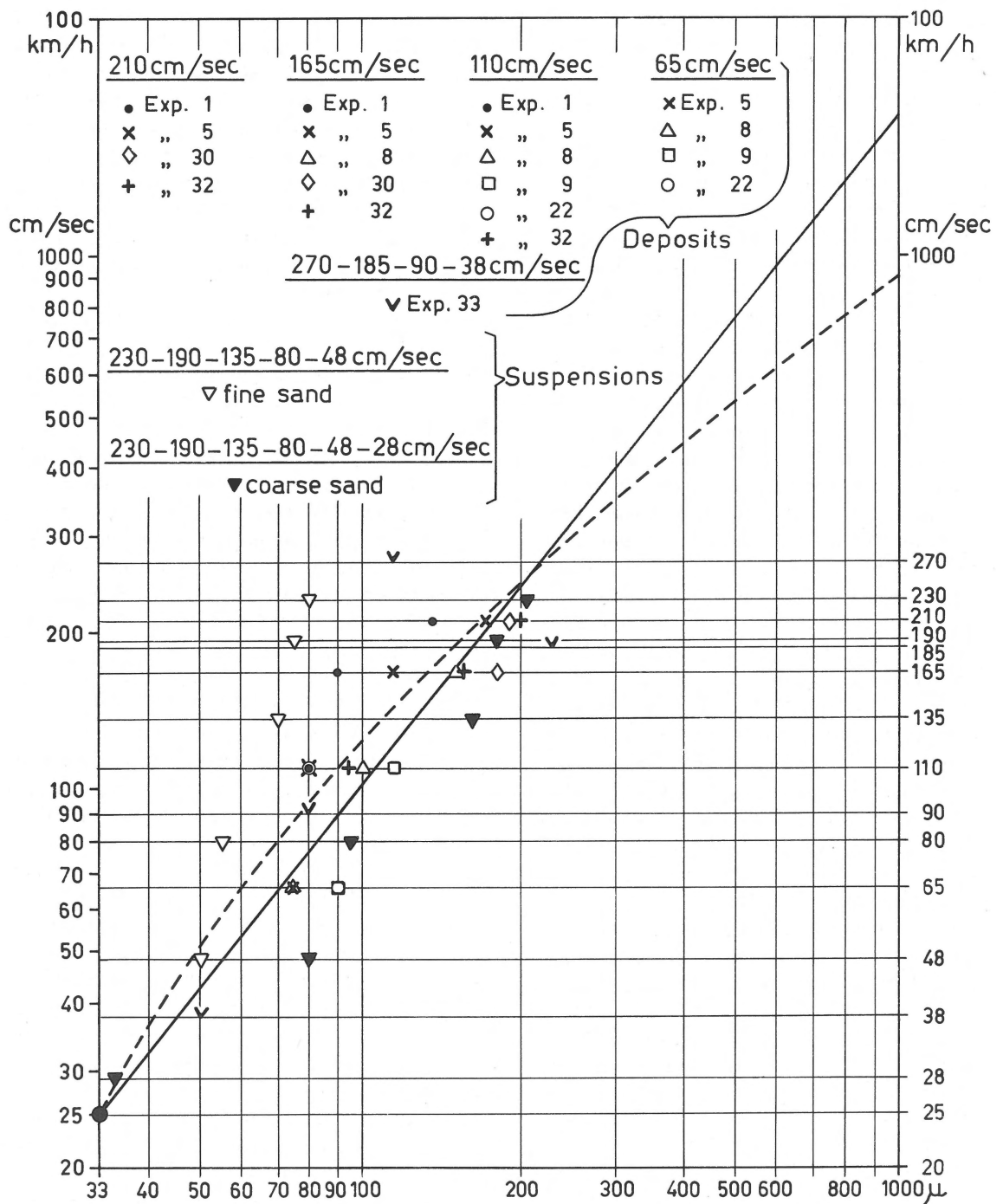


Fig. 13

Relation between current velocity and median grain size >33 microns for (1) Calculated average composition of deposit formed at average velocities (Exp. 1, 5, 8, 9, 22, 30, 32 and 33) as marked at top of diagram. (2) Suspension samples at velocities shown; for the fine grained charges the lowest medians, for the coarse grained the highest medians are recorded. Table V gives some of the values. The dotted line is thought to approach best to average for deposition, but admittedly the extrapolation is guess work.

dent on the grain size distribution of the load (coarser than 33 microns) at high velocity, suspensions at lower velocities will have different compositions, but the amounts will differ only slightly.

(2) There is no interchange with the deposits, as far as can be observed, except during rippling with slowly climbing ripples.

(3) Capacity grows somewhat with the available range in grain size, but presumably addition of coarse grains forces part of the finer material to be abandoned and vice versa.

(4) The deposition is dominated more by original composition and capacity than by competency. This means that all grain sizes are incorporated in the deposit almost with the same grain size distribution as in the suspension just above the bottom. Possibly a suspension with a very high silt content may start by dropping a finer deposit than later on at a lower speed, owing to overloading when the current is still far above competency for a minor coarser part of its load.

(5) There is some concentration in the current of the larger grains towards the bottom. Hence, deposition causes a shift in suspension composition towards the finer sizes. However, the composition of the deposit is so close to that of the suspension that sinuosities in the cumulative curve of both persist from high to low velocities.

The authors offer the following tentative explanation why competency is so ineffectual in deposition. In the current there is a thorough mixing of all grain sizes in the load due to the turbulence. But the larger the grain size the more it is concentrated towards the bottom. In contact with the bottom there is a non-turbulent stratum, that discards all grain sizes indiscriminately. Its load is replenished from the lowest horizons of the well-mixed turbulent part and therefore the deposit contains all grain sizes more or less in the same quantitative relation as in that lowest part.

The absence of erosion and of interchange between current and deposit is due to the overloading of a slackening suspension current and to the somewhat higher velocity needed for erosion than for deposition. When a river is gradually subsiding after a spate the deposition should act similarly to the

development in the flume. But during periods of constant or increasing flow a river is eroding at many points on its bed, and may be depositing in the vicinity. Even when waning, a river always finds some coarser material here and there by the shifting of its bars and channels. By rolling these particles it can mix them with its finer deposits dropping from suspension. Consequently a wide range of sizes is available to a stream, of which the larger ones are transported on the bottom. These can form well-sorted lenses of sediment governed by rolling competency. But the turbidity current has no material at its disposal which has not been carried in suspension all the way to quite close to the point of deposition. A larger grain once it has started to roll, will lag behind the current and the flow sweeping over it is slackening all the time and adding from its own smaller grain size. Hence, wherever a turbidity current arrives coarse fractions beyond the suspension-competency are lacking.

An important question is the current velocity at which a given horizon in a turbidite has been deposited. It is obvious that the limited influence of competency against the dominant role played by the grain size distribution in the original charge must result in a rather loose link between velocity and median of the deposit. Another cause for variation is the large influence of the fine silt and clay on the carrying power.

In Table V the experimental results for the analysed samples of suspensions taken at all three levels and for the calculated deposits are brought together. In Fig. 13 the relation is shown between current velocity and median of calculated deposits (see Fig. 8). Exp. 1 to 22 carried only fine sand; Exp. 1 was clear fresh water; Exp. 5 had a dilute clay suspension; Exp. 8 a medium and Exp. 9 a high clay density; Exp. 22 had a medium density of Wadden Sea clay; the capacity in Exp. 9 and 22 was so high that all the sand was already raised and almost uniformly mixed at 135 cm/sec; Exp. 30 to 33 had a fair amount of coarse sand added; Exp. 30 had a high and Exp. 32 a low clay density; Exp. 33 had a low clay density but a very large amount of silt.

The median of the deposits formed between 190 and 135 cm/sec (average 165 cm/sec) is raised from 90 to 150 microns by increase of the clay density from 0 to 0.1 (Exp. 1-9). It would have reached at least 180 microns if coarse sand had been available, as follows from Exp. 30. Even in Exp. 33 with a

moderate amount of clay and much silt the median for 185 cm/sec is no less than 230 microns.

As the velocity decreases the medians are also reduced. At 210 cm/sec it is around 175 microns, but at 65 cm/sec it is only about 85 microns. The range in the medians also decreases. Thus at 165 cm/sec it is from 90 to 180 microns, at 65 cm/sec the spread is only from 75 to 90 microns. This is presumably a response to the inability of a slow current to raise any but fine particles, whereas a fast current can transport larger particles but may find only fine sediment to pick up. As the measurements were made on samples washed out at 33 microns the range should converge to that size at 25 cm/sec where the competency is about that much (see Table V).

It is logical to assume that high velocities are developed mainly in turbidity currents of high density and that with high velocities erosion will tend to add to that density. This leads to the corollary that for extrapolation to high values of size a curve with upward convexity should be postulated, like the dashed line in Fig. 13. This indicates that very coarse turbidites with a median of 1 mm and hence with plenty of gravel were deposited from currents of something like 10 m/sec, or one third the estimated maximum velocity of the Grand Banks turbidity current of 1929. The median of the suspension at that time would have been 600 microns. The Grand Banks current does not appear to have encountered such coarse material to raise, and one can only guess what the maximum competency was, even though samples are available.

The main difference of the experimental conditions compared to natural turbidity currents is that in the flume only the lower part of the currents is represented. The consequences are, firstly that the main body of a natural current is presumably flowing faster than the average of the experimental current when conditions close to the bottom are similar.

Secondly the average grain size of the current will be less than in the experimental reproduction. The finer grained and more dilute main body of the current will be dropping part of its load into the lower strata represented in the experiments.

IX. NO TRACTION CARPET

The interplay between a river or marine bottom current and its bed tends to produce a traction carpet of rolling and saltating grains. There is no sharp

distinction between saltation and suspension because all suspended particles will touch the bottom now and again, and a saltating grain may collide with another or be caught up by a vortex and make some up- and downward excursions independent of the original jump. Virtually this amounts to temporary suspension. Cohesive particles, like lutum floccules, can thereby stick to the bottom with the result that experimental marine currents up to about 10 cm/sec in touch with the bottom, ultimately become perfectly clear (K u e n e n, 1965).

The behaviour of cohesionless particles in a waning suspension current appears to be different as far as can be judged by the present experiments. Above it was argued that a river is constantly encountering particles that are too large to be carried in full suspension. These have been carried along from a distant source during former spates, or by bottom traction in countless successive leaps from point to point on bars and in positions temporarily outside the shifting channel. A turbidity current is passing all the way over pelagic deposits in which it produces flutings and grooves, thus enlarging its load of lutum. But the coarser deposits of former currents are normally not eroded, so that sand particles are not reanimated by a later flow. Each sand grain makes one uninterrupted journey. Once deposited it tends to be covered straightway by continuing loss from the turbidity current. The reduction in speed of the current from nose to tail likewise renders the lifting up of a deposited grain unlikely. Moreover, the current is overloaded and will not easily pick up grains. The result is that all particles have travelled all the way to the point of final deposition in suspension. Occasionally they may have lightly touched the bottom but they have been immediately whirled back into suspension before coming to a standstill. This deduction is confirmed by the remarkably fine grain of turbidite ripples that formed at normal rippling velocities at a time that there was evidently only very fine sand supplied (K u e n e n, 1967). This will be explained in greater detail in a forthcoming publication (K u e n e n and H u m b e r t, in press).

The main condition for the development of a truly distinct traction carpet is that there are particles available smaller than rolling competency, but larger than suspension competency, so that they cannot leave go entirely of the bottom. The latter condition is not fulfilled in a turbidity current, and for that reason no traction carpet should be present

in the experiment or in a natural turbidity current.

This condition does not exclude a segregation towards the bottom in size and amount of the particles in suspension, more especially the larger ones. The upper part of a turbidity current, that is not represented in the present experimental currents, has upward decreasing velocity so that the gradual drop in carrying power can hardly be doubted. It was, moreover, demonstrated in former experiments with true turbidity currents (K u e n e n and M i g l i o - r i n i, 1950). But even in the present currents, representing the lower part of turbidity currents, the sampling has shown that there is a gradual upward decrease in concentration and in grain size of the sand (see Tables II and IV). In no cases was there a segregation towards the bottom of an abnormally loaded stratum in the currents, not even in the cases where deposition had built up the bed close to the lowest sampling point. Only when the intake of the sampler was situated in a self-made hollow excavated in the bed was there an unusual increase in concentration (see Fig. 4, A, values between brackets).

Visually no thin or thick traction carpet could be observed, not even after the velocity had been held constant for so long that deposition had entirely ceased. A phenomenon somewhat akin to a traction carpet was observed in an experiment with a low lutum density and a very wide range in grain sizes. Every now and then a flock of large grains, one particle thick and a few dozen in length came skipping and rolling along more or less in contact with the floor. At a given moment the group would come to rest suddenly, thus producing a coarse lamina. This appeared to be the mechanism by which the distinct lamination of the deposit was being built up.

On the strength of the above analysis and observations it is maintained that in turbidity currents the load of sand is graded in size and density in the current both upwards and backwards from the nose without any development of a traction carpet. The lamination which develops in the deposits as soon as accumulation falls below about one half centimetre per minute, is the result of selection during the short period that a grain moves forward more or less on the bottom. But this is hardly comparable with the traction of a river.

X. NO EXCHANGE WITH BED

The normal condition in a river is loading to capacity for bottom transport in so far as the grain sizes are available, and underloading for suspension owing to insufficient supply. The result is that there is very little interchange of fine load with the bed, but very active interchange of saltating grains and halting progress (also a kind of interchange) of rolling stock. A shifting channel can erode lutum deposited outside a former channel, but amounts are usually insignificant.

Conditions for a gradually slackening suspension current are different. Saltation and rolling are the final short-lived stages of transport and are enacted almost without interchange. The suspended material is loaded slightly beyond capacity. Hence, there is uninterrupted deposition going on. Even during rippling the ridges are usually of the climbing type and frequently even show deposition on the stoss-side. If there is deposition on these most exposed elements of the bottom relief, the whole area occupied by these ripples must be undergoing upbuilding. Under conditions of upbuilding exchange between bed and current must be absent or insignificant.

The experiments show that the grain size distribution of the deposit depends to a large extent on the composition of the load in suspension. Hence, the composition of the bed is not the factor determining which particles will be accepted and which refused. The dominant part played by the composition of the load can be seen by comparing the marked difference in grain size distribution of the deposits of Exp. 5 and 33. Where the charge of the flume was not log-normal, as in Exp. 32 (Fig. 11) the deposits and suspension were not log-normal either. If the bed is inactive in determining which grains are added, it appears unlikely that there is much exchange between current and load.

When the current is held constant in an experiment a stage develops in which the load also remains constant. This might be more favourable for exchange, but none could be seen to take place.

Once deposition from a waning current has started no flutings or distinct groovings are produced. Below and above the rippled horizon there are no or only planar internal bedding planes in natural turbidites or experimental deposits. It was shown in the experiments that the deposit is extremely hydroplastic and

any irregularity produced with a probe flows back instantly to horizontal like in a liquid. Convolutions are formed by deformation within the bed and below a surface that is smooth or rippled. The most favourable circumstances for return of particles into suspension would be small-scale bottom relief. In this respect also the growing bed of a turbidity current must be less favourable for re-suspension than the more compacted sandy bed of a river.

The liquid drag on deposited grains should grow with the amount of lutum in suspension. But on the other hand the impacts of moving grains should be damped down. The authors see no reason to expect interchange with higher concentrations.

XI. BIBLIOGRAPHY

- Einstein, H.A. and Krone, R.B. (1962) — Experiments to determine modes of cohesive sediment transport in salt water. *Journ. Geophys. Res.*, Vol. 67, p. 1451-1461.
- Hjulström, F. : in Trask, P.D. (1955) — Recent marine sediments, p. 10. *Amer. Assoc. Petrol. Geol.*, 736 p. A symposium.
- Kuenen, Ph.H. (1965) — Experiments in connection with turbidity currents and clay suspensions. *Proc. 17th Symp. Colston Res. Soc. Univ. of Bristol*, Vol. 17, p. 47-74.
- (1966a) — Experimental turbidite lamination in a circular flume. *Journ. Geol.*, Vol. 74, p. 523-545.
- (1966b) — Matrix of turbidites: experimental approach. *Sedimentology*, Vol. 7, p. 267-297.
- (1967) — Emplacement of flysch-type sand beds. *Sedimentology*, Vol. 9, p. 203-243.
- Kuenen, Ph.H. and Humbert, F.L. (in press) — Experimental turbidite ripples, *Sedimentology*.
- Kuenen, Ph.H. and Migliorini, C.I. (1950) — Turbidity currents as a cause of graded bedding. *Journ. Geol.*, Vol. 58, p. 91-127.
- Menard, H.W. (1950) — Sediment movement in relation to current velocity. *Journ. Sedim. Petrol.*, Vol. 20, p. 148-160.
- Sengupta, S. (1967) — Grain-size frequency distribution as indicator of depositional environment in some Gondwana rocks. *Preprints 7th Intern. Sedim. Congr., Britain*.
- Sundborg, A. (1956) — The river Klarälven: a study of fluvial processes. *Geogr. Annaler*, Vol. 38, p. 127-316.