

(Paper No. 4380.)

“Silt.”

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At the end of 1914 the Engineer-in-Chief of the Huangpu Conservancy Board, Captain A. V. H. von Heidenstam, M. Inst. C.E., initiated a continuous silt survey, in connection with an extensive organization for hydrometric observations of all kinds in the Huangpu river, the lowest 20 miles of which forms the harbour of the great port of Shanghai. The conservancy work, undertaken by the Board, is at present confined only to this river, but in the interests of the port a study of the Yangtze Estuary, the southern channels of which constitute the ocean approaches to Shanghai, was instituted in 1914, and has been continued ever since. Gradually the silt survey was also extended to include the lower Yangtze. The entire hydrographic service for collection of all data has, since 1912, been in charge of Mr. E. C. Stocker, B.Sc. Since 1916 it has been part of the Author's duties to analyse the results obtained with a view to discover the relation of the silt content of the water to the régime of the rivers in question. The principal conclusions as to silt have already been published in the Board's reports. [“Hydrography of the Huangpu,” Report No. 1, 1916, and No. 2, 1918; “Report on the Yangtze Estuary”, 1917, and “Hydrology of the Yangtze Estuary”, 1919, and in the Author's Paper to the Engineering Society of China, “Some Problems on Silt”, (1918-1919 Session)].

The Huangpu.—This river (formerly, and still officially, written “Whangpoo”) is a channel about 2,000 feet wide and 30 feet deep at its junction with the Yangtze, diminishing to about 800 feet wide 40 miles up where it bifurcates, one of the channels connecting 20 miles further to the lake system of the central S. Kiangsu province, the other dying away into the very elaborate canal mesh lying between the lake system and the coast. The watershed is about

8,000 square miles in area, and the rainfall exceeds 40 inches, but the discharge is small owing to the high evaporation, large water surface, almost universal use of irrigation, and the small hydraulic gradients. The western watershed consists of a range of hills running from near Hangchow (capital of the Chekiang province) to Chinkiang, a treaty port on the Yangtze 156 miles above the mouth of the Whangpoo. The northern limit is near the Yangtze river, but as there are numerous small canals leading to that stream, there is no definite line of demarcation; on the south and east, the limit is the coast, along which there is a dyke which prevents all passage of water, except for occasional and unimportant sluices.

The Yangtze Estuary, where the Huangpu joins it, is 9 miles wide (maximum depth about 50 feet), not including another channel 5 miles wide further north. The high water coast-line running north and south is about 18 miles due east of the Huangpu mouth. The shore shelves very gradually for many miles out.

There is a strong tide in the Yangtze Estuary at the mouth of the Huangpu, according to the following specification:—

Maximum range	14 feet.	
Spring range (exceeded by only 10 per cent. of all ranges)	10	„
Mean range	7	„
Neap range (exceeded by 90 per cent. of all ranges)	4	„
Extreme rise above lowest low water	18	„ (typhoon).
Rise of spring H.W. above lowest low water	13	„
Rise of Mean H.W. „ „ „	10·25	„
Rise of neap H.W. „ „ „	8·5	„
Least rise of H.W. „ „ „	5·0	„
Extreme rise of L.W. „ „ „	11·2	„
Rise of neap L.W. „ „ „	5·0	„
Rise of mean L.W. „ „ „	3·5	„
Rise of spring L.W. „ „ „	2·25	„
Lowest low water „ „ „	0·00	„
Rise of mean half tide level above lowest low water	about 7·00	„

There is an annual variation of stage in the Yangtze at the mouth of the Huangpu of about 2 feet (due to discharge, wind, and barometric changes).

Discharge measurements have frequently been taken in the Huangpu about 2 miles above the entrance (Pheasant Point) with the following results (p. 402).

The discharge has been deduced from rainfall and float tests as about 7,000 cubic feet per second, corresponding with 315,000,000 cubic feet in a tidal period (one ebb and one flood).

Maximum flood influx	4,235,000,000 cubic feet.
Minimum "	415,000,000 "
Maximum ebb efflux	4,080,000,000 "
Minimum "	1,517,000,000 "
Maximum flood velocity	6·13 feet per second.
Minimum "	1·19 " "
Maximum ebb velocity	4·87 " "
Minimum "	1·72 " "
Mean sectional area at half-tide level . about	62,500 square feet.

The mean sectional area of the Huangpu at half tide diminishes to about 38,000 square feet at 40 miles up stream, and it will readily be apparent that, in view of the actual velocities and the imaginary discharge velocity (less than $\frac{1}{2}$ foot per second), the Huangpu exists in its present dimensions in virtue of tidal currents rather than discharge. Actually flood currents exceeding the ebb currents occur almost right up to the lake system, so that the Huangpu is a tidal swashway rather than a river. The whole watershed right up to the foot of the hills consists of consolidated silt deposited in past millennia from the Yangtze.

Problems.—The following problems in the Huangpu required solution, and warranted the silt investigation :—

- (1) Does the change in silt content during daily, fortnightly, and annual periods support belief in general scouring or erosion of the bed ?
- (2) How is the silt content affected by changes in the tide ?
- (3) How rapidly does the silt settle ?
- (4) Where does the silt now originate, and, if as appears probable, it comes mainly from the Yangtze, how far does it reach ?
- (5) What are the tendencies as to accretion and erosion of a given alluvial river-bed when there is a continuous silt supply ; and what are the limits, determined by accretion and erosion, to which sections may be artificially modified ?

Sampling.—Daily samples were first taken at four places, as follows :—

Mouth of Whangpoo—just outside the mouth of the Huangpu (in the Yangtze).

Outer Bar—just inside ditto (over the bar).

Pheasant Point—2 miles inside.

Han Yeh Ping—at the upper limit of the harbour (15 miles from the mouth).

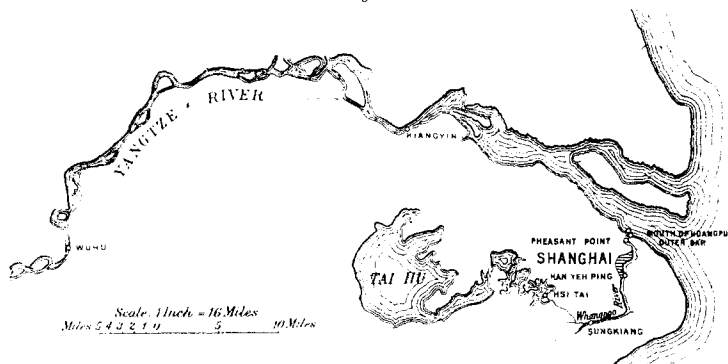
Later two further stations were added :—

Sungkiang—40 miles from the mouth (just below the bifurcation)

Hsi Tai—60 miles from the mouth (at the junction with the lakes)

In order to study simultaneously the Yangtze silt at different points, samples were obtained in that river at a place 30 miles above the mouth of the Huangpu (" Kiangyin ") and at a place 250 miles further up (Wuhu, near the tidal limit in the Yangtze) (*Fig. 1*). In some cases, as consistent or sufficient results accumulated, half weekly or weekly readings were taken instead of daily ones. Slack after high water was chosen as the best time, assuming that

Fig. 1.



SAMPLING STATIONS.

the flood wave had brought in or stirred up the silt. In most cases samples were taken at a depth of 20 feet below the water surface, which represents fairly well the mean depth. A special sampling bottle with a heavy stopper controllable by a cord was generally used. In each case about 500 cubic centimetres of water was obtained, from which two 200 cubic centimetre samples were taken.

To determine the silt content three methods were tried :—

- (a) Filtration.
- (b) Specific gravity.
- (c) Centrifugal settlement.

(Other methods not tried are :—Absorption in kieselguhr or similar material, and colorimetry, in which the opacity of the water is measured optically against a series of standards.)

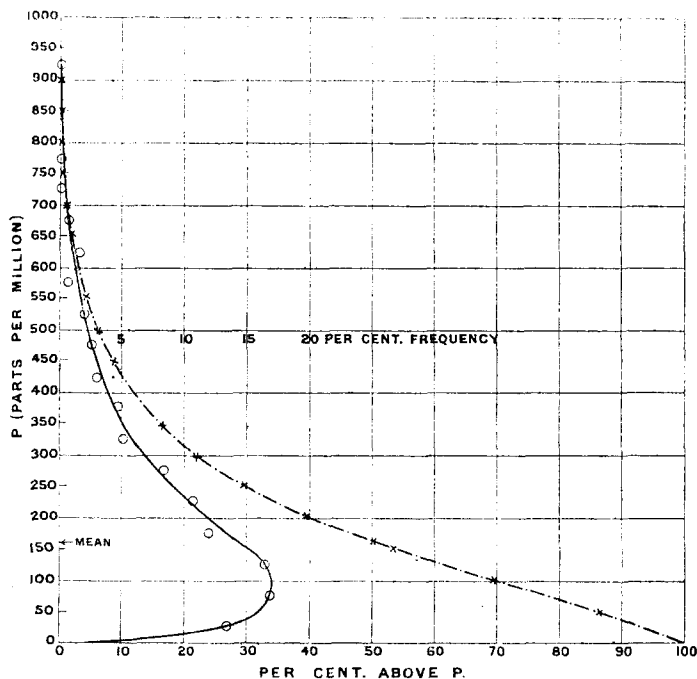
As most of the samples showed less than 1,000 parts per million by weight (1 kilogram per cubic metre ; 57·6 grains per imperial gallon), the actual filtrate to be measured from a 200 cubic centimetre sample was less than 200 milligrams. The balance used read nominally, with a rider, to one-twentieth of a milligram or 1 part in 4,000,000 of the total water sample. There were several practical difficulties in arriving at such precise results. Colloidal silt (about 10^{-4} centimetres in diameter) passes through the filter paper, and needs to be aggregated by ionization. Very weak hydrochloric acid and boiling was found best for this purpose. Considerable trouble was encountered with filter papers, especially during the damp summer weather in China, in spite of careful drying and the use of dessicators. It appears that no accuracy beyond ± 10 parts per million by weight can be expected without tedious methods unsuitable for regular use. For control, determination of the specific gravity both by the regular bottle method and by the Mohr-Westphal hydrometric balance has been used, but it is difficult to secure a higher accuracy than 100 parts per million, chiefly owing to temperature differences during the operations. The Westphal balance readings are still less certain than the results obtained by the bottle method. This specific gravity method is now only retained for determining salt content in the case of specially saline samples. It is very unsatisfactory for silt tests on account of the unknown magnitude of the saline content, and the poor accuracy. Centrifugal settlement with large samples gives a rapid determination of the silt (excepting the colloidal particles), but the deposit is difficult to measure accurately in the settling tubes. It can be strongly recommended for rough determinations. The Author has not sufficient experience with the adsorption or opacity methods. He considers that the latter seems promising, but that it is probable that overestimates can be made when there is a high proportion of silt in a colloidal state, since the transparency is reduced if the dispersion is great. No attempt has been made to determine the variation in the colloidal content, but the average appears to be less than 50 parts per million by weight, which generally means more than 10 per cent. of the total silt content.

Quantities.—The analysis of results covering at least a year was made both by averages and frequencies referred to various arguments. Just inside the mouth of the Huangpu the general average of the silt content is about 200 parts per million by weight, rising to about 600 at spring tides and falling to 75 at neap tides (*Fig. 2*). Outside, in the Yangtze, the values are about 25 per cent. higher, while at the upper end of the harbour they are about 10

per cent. less. Forty miles from the mouth the average is 50 per cent. less, and still smaller values occur at the junction with the lake system. In the Yangtze, at the tidal limit, values from 50 to 100 per cent. greater occur.

Variation.—In the Huangpu there are two annual maxima and minima. The first maximum occurs in February, corresponding with the lowest stage in the Yangtze, and it may reasonably be assumed to be due to the strength of the flood currents which, being less

Fig. 2.



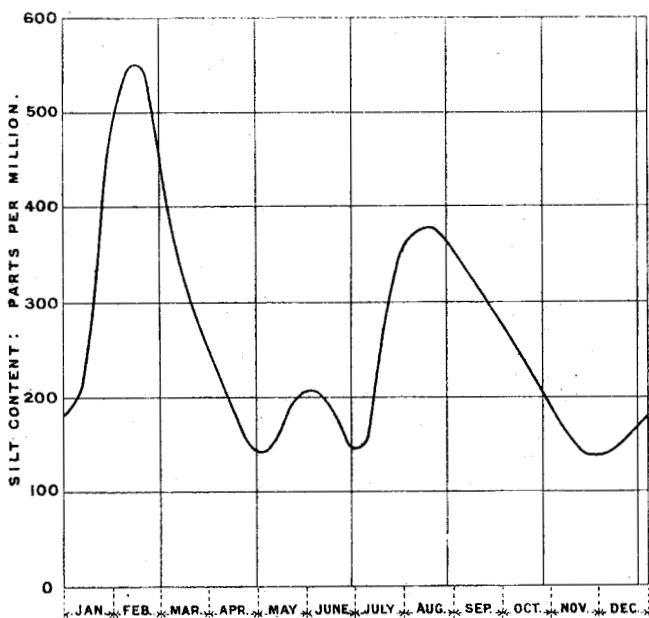
SILT DISTRIBUTION AT PHEASANT POINT.

impeded by the Yangtze discharge, scour up the bed of the Yangtze. Brackishness, which similarly indicates the deep inflow of flood currents, is occasionally observed at this period. The first silt minimum occurs in May, combined with the rising of the river, and is conceivably due to the dilution by the moderately clear Yangtze discharge. The second maximum occurs in August, coinciding with the high Yangtze stage and the single annual maximum silt content of that river above its tidal limit. The second minimum occurs in

November, coinciding with the falling stage and the minimum silt content in the Yangtze above the tidal influence. A similar cycle occurs throughout the Huangpu up to the lake system (*Fig. 3*).

Long averages for corresponding days of the moon show great regularity in the relation between the silt content and the fortnightly tide, the maximum silt content occurring on the 3rd and 18th days of the moon and the minimum on the 11th and 26th days. Individual fortnights show much irregularity in detail, part

Fig. 3.



SILT AT MOUTH OF WHANGPOO (20 FEET FROM SURFACE).
DAILY AVERAGE FOR 4 YEARS.

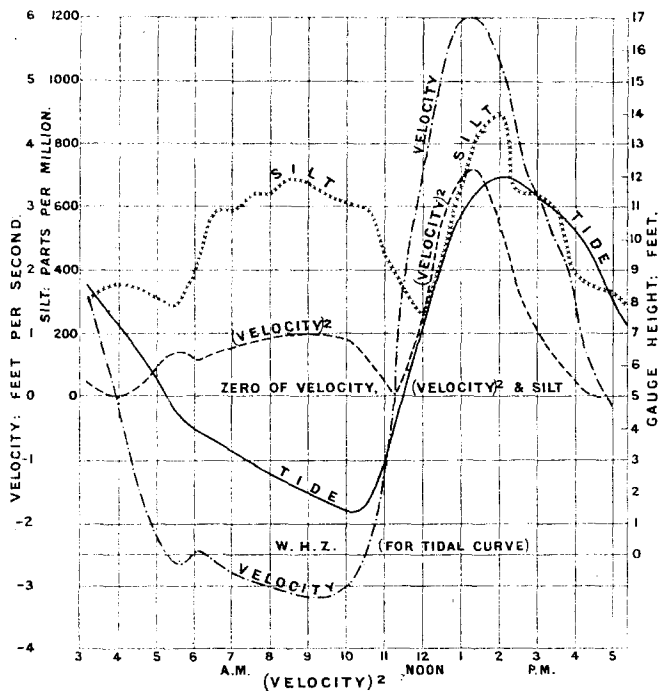
of which is attributable to the diurnal inequality of range which is very marked in Pacific coast tides.

By hourly readings it has been shown that there is a $12\frac{1}{2}$ -hour period in the silt content, but the enormous number of observations necessary have made it impossible to say what the average degree of correlation is. There is rapid increase of the silt content during acceleration of the current and a rather spasmodic decrease during the retardation, but the actual maximum may occur before, at, or after the "full" flood, and there has not usually been much

diminution at slack after flood (which is the standard moment of observation for daily sampling) (*Fig. 4*).

Numerous observations have failed to show any regular correlation with the depth. It appears, however, that during steady flow the distribution is almost uniform, whereas, during spring tide acceleration, the content near the bottom may be four times that near the surface. It must, of course, be here observed that such

Fig. 4.



VARIATION IN THE SILT CONTENT OF YANGTZE WATER AT THE MOUTH OF THE WHANGPOO IN A WHOLE TIDE.

observations can only be of value in long uniformly-sectioned reaches, since the silt content, except quite close to the bottom, may originate at a great distance away.

No appreciable differences across the width of the river have been determined.

Velocity of Descent.—General hydrodynamic principles of “turbulent” resistance and Stokes’ rule for “viscous” resistance indicate that, for spherical particles having a specific gravity of 2.5

descending in water by reason of their own weight, the maximum velocity (which is very rapidly reached) is¹

$$v = \sqrt{3924d + \left(\frac{0.24^2}{d}\right)} - \frac{0.24}{d}.$$

(v = velocity in centimetres per second).

(d = diameter in centimetres).

Examples :—

$d = 1.0$ centimetres ; $v = 62.4$ centimetres per second.

$d = 0.01$ „ „ $v = 0.8$ „ „

$d = 0.0001$ „ „ $v = 0.00008$ „ „

This formula includes both hydrodynamic and viscous resistance. In the case of colloids the viscous resistance predominates, so that up to a value $d = 0.01$ centimetres, it is quite accurate enough to use the expression $v = 8175d^2$, or $10,000d^2$ for irregularly shaped particles.

The majority of the samples show that the silt content in excess of 100 parts per million settles 20 centimetres in about an hour, another 50 or so in about 24 hours, and the colloidal remainder in from 3 days to a week. The important part of the silt certainly does not settle much faster than 0.01 centimetres per second, which roughly corresponds with a diameter of 0.001 centimetres. Microscopic examination shows particles of this order (one-tenth of a millimetre). It is obvious that the total descent during a tidal period ($12\frac{1}{2}$ hours) is generally less than 15 feet, so that, apart from downward currents, much of the silt entering such a tidal river with a flood wave does not reach the bottom before it leaves again on the ebb.

Tidal Oscillation and Silt Discharge.—The maximum length of run of a float on the flood current in the Huangpu is about 70,000 feet, and as the corresponding ebb travel is, with rare exceptions, longer than the run on the flood, this would be the greatest distance from the mouth to which Yangtze silt could be shifted in one step. If silt so displaced settles and is not carried back during the following ebb, some subsequent flood may take it further. Apart from this consideration all silt above that point must originate from the bed of the stream. The bed is practically stable so that the silt content excess at spring tides over that at neap tides is presumably largely due to temporary erosion. As there is a small but appreciable

¹ This formula assumes that both the turbulent resistance and the viscous resistance exist at all velocities.

discharge there must be an outward flow of silt, but it is not clear whether this exceeds the minute supply brought down by the discharge.

A spring tide may bring in 4,000,000,000 cubic feet of water, carrying about one-thousandth the volume of mud.¹ This, if it were wholly deposited on the bed in the 70,000-foot flood travel over the width of about 2,000 feet, would make a layer $\frac{1}{25}$ foot thick, or about 20 feet per annum. Actually there is no such effect except on convexes and in cul-de-sacs, where an accretion of about 2 feet per annum may occur. Dredged hollows in certain places may accrete at something like the tremendously large rate given.

The discharge of 315,000,000 cubic feet per tide, carrying perhaps one two-thousandth of its volume of mud, must actually convey some 150,000 cubic feet of mud per tide, about one-twenty-fifth the efflux of the spring ebb, and perhaps one-tenth of that of a neap ebb. This small quantity may originate as above mentioned from the remote hilly parts of the watershed (which is improbable as the lakes provide immense settling basins) or more probably by erosion of the bed and banks of the river above Shanghai, which appear fairly clearly cut.

Bottom Creep.—The existence or otherwise of a mobile layer of bottom mud has not been fully decided. Accretion measurements in the river in some cases indicate more than can be accounted for by deposition of the water-borne silt, but the possibility of a steady precipitation from the moving water, and of underestimation of the silt content prevent certainty.

In a column of water 50 feet high, containing one-thousandth the volume of mud, there is only enough mud to form a layer $\frac{1}{250}$ foot thick, and on the face of it an additional mobile layer of such a thickness at the bottom (thereby doubling the total silt in motion) seems probable, but, from a consideration of the behaviour of mud, the Author is inclined to the opinion that no such layer having a considerable velocity can exist. That a stratum next to the bottom, perhaps 1 inch deep and carrying upwards of 5 per cent. by volume of silt ($=\frac{1}{250}$ inch of mud), may exist, is possible, but it seems probable that to stir up and maintain in suspension any such high proportion of mud requires a contact velocity such as does not exist near the bottom.

The Question of Saturation and Equilibrium of Section.—The last consideration leads to the question of saturation. The opinion has often been expressed by river engineers that there is a labile

¹ Including capillary water, density 1.75; see below.

equilibrium such that when additional silt is added to a stream, other suspended silt is precipitated more rapidly, or again that there is a steady rain of silt on to a bed which may be just compensated by erosion (Kennedy's Indian Canal formula).¹ The Author has made experiments with silty water which indicated that the rate of precipitation (loss of silt per unit volume per unit time) varies as some power of the silt content not less than the third, but the question in an actual river is so bound up with that of the depth of the water, vertical currents, horizontal velocity, and the fact that the bottom is both the sink and the source of the silt, that he cannot see how to apply this conclusion. As to Kennedy's theory, it is difficult to discover why any silt should settle at all, concurrently with and in the same place as the erosion. Also, as long as the kinetics of turbulent fluid motion in open channels is unknown, it is impossible to know how the silt travels in relation to the bed, and consequently where and how fast it precipitates. Several lines of thought suggest themselves. Firstly, with regard to the saturation, the colloidal theory shows that ionization (by sunlight, bacteria, radioactivity, friction, etc.) may cause aggregation of colloids. This alone would explain something, since the particles may be eroded or be in suspense as colloids and descend as aggregated and (relatively) large masses which do not erode. Again all suspended particles have surfaces, films of compressed ("adsorbed") water. (These may be somewhat erroneously but picturesquely conceived as concentric shells of water sufficient to explain viscous fall from hydrodynamic resistance or hydrodynamic fall from viscous resistance. One may suppose that when two such shells come in contact the enclosed suspensoids are drawn together and are embraced in one adsorbed shell). Alternatively one may suppose that the bottom of a channel is steadily eroding while the banks are accreting and that the section is maintained by lateral bottom creep, the silt thus flowing laterally from centre to sides through the water and back again on the bed, or even that the bottom rises and the shores sink. A very important point is that silty and clay beds (i.e., material containing a high proportion of colloids) will bear very much higher velocity than sandy beds. This may occur without perceptible erosion, and is obviously due to cohesion. Using the well-known formula for fluid resistance :—

$$R = fAV^2 \begin{cases} f = 0.005 \text{ lbs. per square foot.} \\ \quad = 0.0025 \text{ dynes per square centimetre,} \end{cases}$$

¹ Minutes of Proceedings. Inst. C.E., vol. cxix, p. 281.

the following argument may be used :—

If the grains be held in place only by mutual cohesion, the least drag which will move one grain is of the order of one inter-molecular bond (about 10^{-6} dynes).¹ Equating (using c.g.s. units)

$$10^{-6} = 0.0025 \, d^2 \, v^2$$

$$v = \frac{0.02}{d} \text{ centimetres per second.}$$

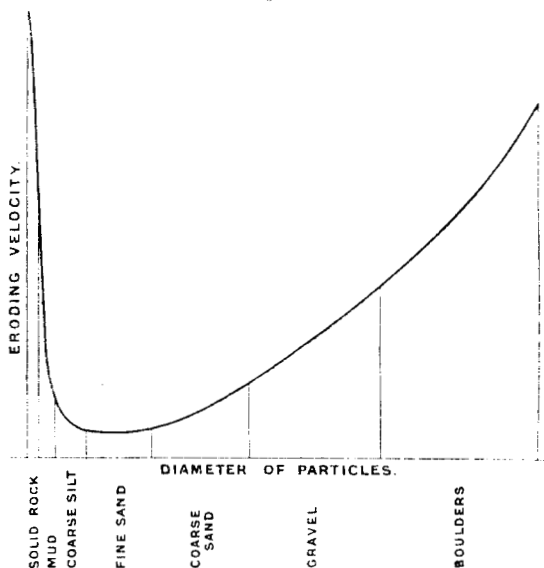
This means that when the velocity has this value it is capable of exerting a drag of one-millionth of a dyne on a particle whose diameter is d , and since that is about the bond between two juxtaposed molecules, it is probable that stable cohesion, if it exists at all, cannot be less than this between two adjacent particles (not molecules). Hence erosion velocity should be at least the formula value. Contrary to the usual erosion rule, (which merely contemplates gravity and friction) the velocity here increases as the grain size diminishes, becoming extremely large for molecular grains such as those in solid rocks. Thus for silt 0.001 centimetres in diameter the velocity required to overcome cohesion is 20 centimetres per second, but for particles 0.0001 centimetres in diameter it becomes 200 centimetres per second. These are actual limits of velocity and grain-size in the Huangpu and Yangtze. The formula neglects gravity and friction, but these, of course, must be included when dealing with coarse sand and will then be found to preponderate. As a result there is a critical value of the diameter of grains corresponding with a minimum erosion velocity, and the erosion velocity is larger for particles whose diameter is either smaller or larger than the critical (*Fig. 5*).

The mud which forms accretions, bed and banks in the Huangpu is of an average density of about 1.75. The dried and powdered silt has a bulk density of about 1.25 and a grain density of about 2.75. This corresponds with a water content of about 60 per cent. by volume, or 35 per cent. by weight. Except under considerable pressure this form is very stable. This fact, together with the moderate degree of plasticity, indicates an appreciable proportion of colloidal particles. The colour of the mud is bluish black, and, probably owing to the high water content, the mud has a small angle of repose (1 in 3 occurs in the river-bed), and it transmits pressure like a viscous fluid. When above the ground water level

¹ The author's Papers on "Cohesion," *Proc. Phys. Soc.*, 1914-1918; "Science Progress," Jan., 1918; "Phil. Mag.," Aug., 1920.

and exposed to solar radiation, it dries and becomes a light brown in colour. Probably some oxidation occurs, as the physical properties of the brown mud are not the same as those of the blue. Chemically the silt consists principally of silica and metallic silicates of practically inert character. According to practical tests made by the Board's Construction Department, the frictional adhesion to piles is about 300 lbs. per square foot, and above ground water level it will bear a load of about 1 ton per square foot superficial pressure over a large area (as in foundations) without settling more than 1

Fig. 5.



VARIATION OF ERODING VELOCITY WITH SIZE OF PARTICLE.

or 2 inches, provided that the surrounding area has been free to dry for some time, or is slightly loaded.

Conclusions.—As will be seen, the problems which were posed have not been wholly solved, but the following general conclusions are indicated :—

(1) Cohesion and colloid phenomena play a very important part in the suspension, aggregation, and erosion of silt, and physicists can render assistance to engineers by throwing more light on the laws of molecular force in such cases. Very complex processes of simultaneous erosion, accretion, lateral sliding, and vortical stream

motion, must be contemplated in regard to the equilibrium of silting river-beds.

(2) In tidal estuaries, old silt which has been stirred up may be even more important than the fresh upland supply.

(3) Bottom creep is probably very small in silt river-beds owing to the cohesion. This is not fully demonstrated, but the Author is satisfied that the effect is less than that in fine sandy beds.

The Author is indebted to Captain von Heidenstam for permission to use the Whangpoo Conservancy Board's extensive records, data, and reports relating to silt, in the preparation of which he himself has participated.

The Author understands that, while it is Captain von Heidenstam's intention to continue certain of the extensive hydrometric surveys, the work on the silt surveys will henceforth be concentrated on obtaining continuous records at one or two points in each of the two rivers, and on analysing the laws of silting and scouring for application to the various practical propositions with which the Board is likely to be faced in its present and future river and harbour work.

The Paper is accompanied by five tracings, from which the Figures in the text have been prepared.
