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Sediment Transportation by Running Water and the Design of Stable Channels in Alluvial Soil.

By

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The flow of water in rivers and canals transports solid material along the bottom or in suspension. As a rule, stones, gravel and coarse sand are transported as bed-load and the finer particles, i.e., medium or fine sand and silt are carried on with a certain distribution from the bottom to the surface of the water. Studying the suspended material in different layers of rivers and canals, it was found that those particles with a smaller diameter than 0.07 millimeter generally are uniformily distributed from the bottom to the surface and that most of the particles with a bigger diameter will be near the bottom and only a very small part of them in the surface layer.

Out of hundreds of diagrams of silt distributions taken at different places, a few examples only are given for illustration in fig. 1.

Roughly speaking, it may be said that the distribution of the finer material occurs in parallelograms and that of the coarser in triangles.

Observing this, the conclusion was deducted that there exists a fundamental difference in the way of transportation of the finer particles and the coarser ones and due to this fact they are termed hereafter as *floating* and *sinking* material respectively.

It would appear that to transport the so-called floating material no amount of energy is needed by the running water, but to transport the sinking material, it costs energy to the stream.

With this in mind, it is obvious that there cannot exist any relation between the mean velocity of a stream and the total amount of suspended material it can carry, but that there may be a relation between the mean velocity and the sinking material only.

For that reason, the finer particles with a diameter of less than 0.07 mm were sieved out of the samples taken from several flows, the amount of sinking material was then weighed and plotted against the mean velocity. The result obtained in one specific case can be seen in fig. 2, which shows how the capacity to transport the sinking material increases with the velocity. Approximately, the concentration of the sinking-material was ;

$$G_s \,/\, G_w = V^4 \,/\, 2000 \qquad \text{(see fig. 2).}$$

Curves like this will be of value in many cases, e.g., for irrigation and drainage designs, as they will enable one to find the approximate charge of sinking material that a flow is able to carry.

Theory.

Firstly, the flow of clear water should be dealt with. Let :

(a) the specific weight $= S_w$

(b) the mean velocity $= V$

(c) the slope $= i$

(d) a volume of water $= V_w$

This volume of water loses per sec. during the flow, a potential energy equal to $V_w \ S_w \ i \ V = G_w \ i \ V$, where $G_w = V_w \ S_w$.

When the water flows with a uniform velocity, the lost potential energy equals the frictional energy.

Secondly, the flow of silt-laden water must be considered, where to V_w is added a volume of silt V_s with specific weight S_s. The particles are assumed to be of the same size and of such diameter that their fall velocity in water is W m/Sec.

In that case, the mean velocity of the mixture of water and silt generally will differ from the mean velocity of clear water.

Let the new mean velocity be denoted as V' m/Sec. The quantity of energy required to hold the particles in suspension is $V_s \ (S_s - S_w)W$ and the loss in potential energy per sec will be :

(i) for the particles $V_s \ S_s \ iV'$

(ii) for the water $V_w \ S_w \ iV'$

These losses in potential energy are used to keep the particles in suspension and also to overcome the frictional losses.

In case of silt-laden water with a mean velocity V'm/Sec the frictional losses will amount to :-

$$V_w \ S_w \ iV' \ (V'^2/V^2)$$

This is based on Chezy's law, assuming that RC^2 is not affected too much by the quantity of transported silt and the frictional losses change only when there is a change in the velocity of the water without being affected by differences in viscosity, normal velocity distribution and turbulence.

Now, according to the law of conservation of energy :

$$(V_s\ S_s + V_w\ S_w)\, iV' = V_s\ (S_s - S_w)\ W +$$

$$V_w\ S_w\, iV'\ (V'^2 / V^2) = G_s\ W\ (S_s - S_w) / S_s +$$

$$G_w\, iV'\ (V'^2 / V^2)$$

for $(S_s - S_w) / S_s = 0{\cdot}6$ we get :

$$G_w\ iV' - G_w\, iV' (V'^2 / V^2) = 0{\cdot}6\ G_s\ W - G_s\ iV'$$

$$\text{or } G_w\, iV'\ (1 - V'^2/V^2) = G_s\ (0{\cdot}6\ W - iV')$$

$$G_s / G_w = (1 - V'^2 / V^2) / (0{\cdot}6\ W / iV' - 1)$$

G_s / G_w is the concentration of the suspended matter in the water and V'/V is the ratio between the mean velocities of water with and without silt.

It can be seen from the derived equation that in the case where $0{\cdot}6\ W = iV'$ then $V' = V$ and G_s / G_w becomes 0/0, so indeterminate. In other words, an indeterminate number of particles can be transported by the water without changing its velocity if $0{\cdot}6\ W = iV'$. This result is in accordance with the findings of several investigators. They were of the opinion that there exists no relation between the mean velocity and the suspended silt-charge. In the case where $0{\cdot}6\ W < iV'$ then $V' > V$. This means that by adding very fine material to a stream its velocity will increase. This fact was also observed several times.

The particles with a fall velocity $W < iV'/0{\cdot}6$ are called floating material and those for which $0.6W > iV'$ are termed sinking material. For the former, no "saturation" will occur, but for the latter, according to the given formula, the concentration will depend upon the velocities of clear and silt-laden water, the slope of the stream and the fall velocity of the particles. The following table gives some examples of cases in which $0{\cdot}6W = iV$.

From this table, it is to be seen that for the cases given the limit between sinking and floating material is varying theoretically between the diameters 0·01 and 0·1 mm.

In practice, however, when $V > 0{\cdot}5$ m/sec all silt particles smaller than 0·07 mm appear to behave as floating material.

The question now is, whether it is a good policy to have all the canals of an irrigation system of the same iV to prevent silting, According to the

Discharge Q in m^3/Sec	Velocity V in m/Sec	Breadth b in m	Depth h in m	Slope i in 10^{-3}	Vi = 0.6W	Fall Velocity W in mm/Sec	Diameter in mm.
500	3	41	4·1	1·008	3	5	0·076
100	2	22·2	2·22	1·45	2·9	4·9	0·076
100	1·5	26	2·6	0·58	0·87	1·45	0·04
100	1	31·6	3·16	0·20	0·20	0·35	0·02
2·5	0·5	3·15	1·05	0·19	0·095	0·15	0·013
0·3	0·35	1·06	0·58	0·29	0·10	0·16	0·013

above mentioned theory of the conservation of energy and as Lacey's formulæ suggest ($V \cdot S = 4 \cdot 3\ f^2\ 10^{-4}$ = Constant, where V is the velocity in ft/sec and S is the slope or $Vi = 1 \cdot 4 f^2\ 10^{-4}$ in the metric system) this seems probable. However, it will depend upon it being proved that V′/V is a function of the product i.V and provided care is taken to keep the equivalent fall-velocity equal for all the outlets of the canal system.

The ratio V′/V indicates the influence that the transportation of silt will have on the coefficient in the formulae for the mean velocity, since V′/V = C′/C = K′/K for the Chezy's and Manning's formulae respectively. As velocity will change a few per cent only (which will be proved later) and when unity is neglected in comparison with 0.6 W/iV′, which may be done if the sinking material only is taken into account, then :

$$G_s \ / \ G_w = \left\{1 - (V - \Delta V)^2 \ / \ V^2\right\} \ / \ \left\{- 1 + 0.6W/i(V - \Delta V)\right\}$$

$$= (2\Delta V/V) \ / \ (0.6W/iV)$$

$$= i\Delta V/0.3W$$

So, the concentration is proportional to the product of slope, and, decrease in velocity and inversely proportional to the fall velocity of the particles. Now considering that the decrease in velocity (ΔV) will mainly depend upon :

Re, Reynold's number, $Re = VR/\partial$

E, the magnitude of the surface irregularity

R, the hydraulic mean depth and

V, the mean velocity, then the dimensionally homogenous exponential equation :

$\Delta V = c \ Re^{m} (E/R)^{n} V$ will conveniently illustrate the phenomenon.

Therefore : $G_s \ / \ G_w = ciRe^{m}E^{n} \ V/0.3 \ WR^{n}$

and as $V = C_1 \ (g \ Ri)^{1/2}$ or $i = V^2 \ / \ C_1^2 \ g \ R$

$G_s \ / \ G_w = cV^{3+m}E^{n} \ / \ 0{\cdot}3W \ C_1^2 \ g \partial^{m} \ R^{-m+n+1}$

Furthermore as : $C_1^2 \ g = C^2$ and according to Strickler :

$C = 25R^{1/6} \ /E^{1/6} \quad C_1^2 \ g = 625 \ R^{1/3} \ E^{-1/3}$

$G_s \ / \ G_w = c \ E^{n+1/3} \ V^{m+3} \ /18{\cdot}75g\partial^{m} \ WR^{-m+n+4/3}$

From the experiments of fig. 2 it may be concluded that $m = 1$ so that : $G_s/G_w = c \ (E/R)^{n+1/3} \ V^4 \ /18{\cdot}75g\partial W$

Now assuming $n = 1/3$ then $G_s/G_w = c(E/R)^{2/3} \ V^4/18{\cdot}75g\partial W$, which indicates that for a given wall-roughness (E) and fall velocity (W), $V^4/R^{2/3}$ or $V^6 \ /R$ must be taken as a constant for the various canals of an irrigation system to enable all of them to transport an equal concentration of sinking material.

However if $n = 2/3$, then $V^4 \ /R$ should be the constant and when $n = 1$ the constant should be $V^3 \ /R$ to prevent silting up of the canals. From Lacey's formula, based on experience in the Punjab can be derived $V^2 \ /R = 4/3 \ f$. So according to Lacey $V^2 \ /R$ should be taken as the constant, in which case the equivalent for n would be 5/3. And if we replace in the classic emperical equation $V = cd^{0{\cdot}64}$ produced by Kennedy in the year 1895 $d^{0{\cdot}64}$ by $R^{2/3}$ then $V^{3/2}/R$ is the constant and n would be equal to 7/3 even.

As long as the necessary experiments concerning the transportation of sinking material in canals with various depths have not been carried out a choice must be made out of either $n = 1/3$, $2/3$, 1, $4/3$, or $5/3$.

Provisionally let $n = 1$, which, physically speaking, is the most probable value, then :

$$G_s/G_w = cV^4\ (E/R)^{4/3}\ /18{\cdot}75g\partial W.$$

and $\Delta V/V = c\ Re\ (E/R)$

The percentage of the velocity or of the energy (viG_w) which will be spent for the transportation of the sinking material depends upon the degree of turbulence and is proportional to the Reynold's number and the relative wall-roughness.

Now, what will be the percentage of this decrease in velocity ? Considering :

$$G_s/G_w = cE^{4/3}\,V^4\ /18{,}75g\partial WR^{4/3}$$

then, when : $R=2m$, $E=5{\cdot}10^{-2}m$ and $W= 21.0'^{-2}$ m/Sec.
$G_s/G_w = cV^4/\ 507\partial.$

G_s/G_w is also according to the experiments of fig. 2, where the hydraulic mean depth on an average was about 2m and the equivalent fall velocity 0·02 m/Sec, equal to $5{\cdot}10^{-4}\ V^4$.
Therefore :

$$c=0{,}25?.$$

and $\Delta V/V = c\ Re\ (E/R) = cEV/\partial = 1{,}25\ V/10^{-2}$
Hence, if V=1 m/Sec $\Delta V/V=1,\ 25\%$
and if V=2 m/Sec $\Delta V/V=2{,}5\ \%$

This shows that the effect the suspended sinking material produces upon the velocity of the transporting flow is small which had to be proved.

Moreover, the equation for the concentration of sinking material can be written now as : $G_s/G_w = V^4\ 750\ (R/E)^{4/3}\,W.$

And as normally : $W=2{\cdot}10^{-2}$ m/sec and $E=5{\cdot}10^{-2}$ m,

$$G_s/G_w = 1{,}25V^4\ /1000\ R^{4/3}$$

$$\text{or : } G_s/G_w = 2{,}125V^2\ i$$

which formula is very attractive from a practical point of view. So far a homogenous medium only has been considered. In the case of a heterogenous medium, then the following procedure should be adopted :

A material is now introduced with a fall velocity W_0 equivalent to $\Sigma W/n$, where n is the number of different categories of equal weight contained in the heterogenous medium.

Previously, only the suspended material has been dealt with. For, an estimation of the bed-load Meyer Peter's formula can be used :

$$q^{2/3} \ i/d = 17 + 0,4 \ g^{2/3} \ /d.$$

where q = discharge in kg/Sec per m bed width

g = quantity of bed-load in kg/Sec per m bed width

d = an average diameter of the particles in m.

In irrigation canals and the lower reaches of rivers in alluvial soils the bed-load will be small in comparison with the suspended matter ; normally, not exceeding 5% of the latter. The total of the bed-load and the sinking material which a specific canal is able to transport will give an idea about its silting up or scouring out, provided it is known how much sand and silt is introduced in the canal at its headwork.

Practical Applications.

The above given theories in general will be of importance when designing irrigation canals.

Also, they can be used in special cases, *e.g.*, for the replacement works which will have to be built in West Pakistan now that the Water Treaty with India has been signed (19th September, 1960).

Seven major new link canals having a total length of about 400 miles with capacities varying from 6,500 to 21,700 cusecs must be constructed to convey irrigation water from the Rivers Indus, Jhelum and Chenab to the Rivers Ravi and Sutlej. If the capacity of those links to transport sinking material (particles bigger than 0·07 mm.) in the long run equals that of the river at the place where the water is taken off, then neither sand excluders nor desilting works will be necessary. If the transporting capacity is higher there will occur a certain amount of scouring in the canal and if that capacity is less, then silt excluders will have to be constructed to sluice away the difference in quantity of sinking material the river and the canal are transporting in suspension, otherwise silting up will occur. The larger the hydraulic radius of the canal, the higher the water velocity and not only the less the earthwork to be dug will be but, what is even more important, the larger the quantity of sinking material that can be transported. The slopes of the canals mostly being flatter than those of the rivers, *i.e.*, 1/7 to 8,000 for the Rasul-Balloki Link to 1/4 to 5,000 for the Rivers Jhelum and Chenab, the canals ought to be designed with more favourable hydraulic cross sections then prevailing in the rivers ; if possible deep enough to reach the same silt transporting capacity. However, if the soil at some places along the alignment of the canal to be dug is very sandy, investigations and calculations in the soil mechanics laboratory may lead to a more shallow profile with regard to stable banks. For these stretches the slope then can be taken steeper so that the same value of V^3/R or $V^2 \ i$ or $R^2 \ i^3$ is obtained for the different parts.

Example 1.

1. *River.*

Discharge	$Q_1=4000\ m^3/Sec$	=140,000 Cs.
Hydraulic mean depth	$R_1=2{,}25$ m	=7·4 ft.
Mean velocity	$V_1=1$ m/Sec	=3·28 ft./Sec
Slope	$i_1=1/5000$	=1/5000

2. *Canal*

in Sandy Soil.

Discharge	$Q_2=400\ m^3/Sec$	=14,000 Cs.
Hydraulic radius	$R_2=3$ m.	=9·84 ft.
Mean velocity	$V_2=1{,}10$ m/Sec	=3·61 ft./Sec
Slope	$i_2=1/6000$	=1/6000

3. *Canal*

in Clay Soil.

Discharge	$Q_3=400\ m^3/Sec$	=14,000 Cs.
Hydaulic radius	$R_3=4{,}50$ m	=14·76 ft.
Mean velocity	$V_3=1{,}26$ m/Sec	=4·1 ft./Sec
Slope	$i_3=1/8000$	=1/8000

In all of the 3 cases : $V^3/R=0{,}444$

$V^2\ i=0{,}00020$

$R^2\ i^3=4{\cdot}10^{-11}$

The concentration of sinking material transported in the river as well as in the two different canal stretches will be, assuming : $W_o=\Sigma W/n=2{\cdot}10^{-2}$ m/Sec and $E=5/10^2$ m, $G_s/G_w=V^4/800\ R^{4/3}$ = constant = 0,4 kg/m^3 = 0,4 g/l or 400 mg per litre.

Thus, the conclusion can be drawn that the sediment carrying capacity of a canal with a shallow cross section is lower than that of a deeper one with equal slope.

Rivers follow the same trend. Where they have formed a wide shallow profile, a steeper slope is needed to transport the same quantity of material than required for the more narrow deep stretches.

Example 2. Marala-Ravi Link.

The Marala.Ravi (M.R.) Link was completed in the year 1956 and from that time up till October 1960, water has flowed in it only during the 5 summer months from May to October. The discharges varied from 6,000 to 22,000 Cs. The sinking material content of the water taken off from the River Chenab has been practically the same as that of the Chenab just upstream of the barrage and varied accordingly from 0·25 g/l for low discharges to 2·5 g/l for a discharge of 125,000 cs and 5 ft./Sec velocity. During higher floods the gates of the canal were closed. The slope just upstream of the barrage is 1/2500 so that when the hydraulic mean depth at this point is 15 ft. a mean velocity of 8 ft./Sec will occur. The sinking material content under such circumstances will be about 5 g/l. The M.R. link has been designed according to Lacey's formulæ with a silt factor f=0·98. Its hydraulics are as follows :—

$$S=0{\cdot}00010$$

$$D=13{,}8 \text{ ft.}$$

$$B=345 \text{ ft.}$$

$$A=5{,}000 \text{ Sq. ft.}$$

$$P=390 \text{ ft.}$$

$$Q=20{,}000 \text{ Cs.}$$

$$R=13 \text{ ft.} =4 \text{ m}$$

$$V=4 \text{ ft./Sec} = 1{,}22 \text{ m/Sec}$$

According to the above given theory the concentration of the sinking material, $G_s / G_w = V^4 / 800R^{4/3} = 1{\cdot}22^4 / 800{\cdot}4^4 = 0{\cdot}433$. Thus, the sinking material carrying capacity of the existing M.R. Link is only 0,433 gram per litre at full supply. During the year 1960, 16×10^{10} cub. ft. have flowed through the M.R. Link. The average content of the coarse plus medium sand (particles with size greater than 0.07 mm) was 1.1 g/l. Therefore, 1100−433=667 mg/l must have settled down. This amounts to a total of 7·2 crores c. ft. (2 million m^3) for the year 1960. According to measurements in the canal, the silting up in 1960 was about 7 crores cub. ft., which figure is in close accordance with the calculations and indicates the practical applicability of the sinking material theory. Since the opening of the canal 4 years ago, the silting up has been 19 crores cubic ft. In 1959, a very wet year, during the 4 months May, June, August and September the average silt content of the water taken off was 1,25 g/l and in July the gates had to be closed for most of the time due to high floods in the river. The silting up of the M.R. Link in 1959 may have increased by another 7 crores cubic feet. In 1956 during summer only 14,000 Cs flowed through the canal and in 1957 only 10,000 Cs during 1·5 months. The silting up in the first 2 years of exploitation may be responsible for the deposit of the remaining 5 crores cub ft. sand. At present, from the original depth of 13.8 ft. of the M.R. Link 8 ft. has been lost at the head of the canal and the silting up extends over a distance of about 20 miles.

If the M.R. Link had not been designed with a shallow cross section but with a depth in the centre of 35 ft. a bed-width of only 10 ft. and sides slopes of 1:4 over 20 ft. 1:3 over 30 ft. and 1:2 over 40 ft. then the width at the water surface would have been 190 ft. which is half of the existing one and the cross section would have been 3,950 sq. ft. only. Therefore, the earthwork would have been 1,000 cub. ft. per foot run less. The hydraulic radius then would have equalled 19·36′ = 5·9 meters and with the same slope 1:10,000, a mean velocity of 5.2 ft./Sec = 1.59 m/Sec would have been obtained; resulting in a sediment transporting capacity of 755 mg/l. Although this is 322 mg more than the 433 of the existing canal, it is still a 400 mg/l less than what the river transports. Thus, a sediment excluder, a silt extractor or a settling basin at the head of M.R. Link is an unavoidable necessity. As it is impractical to change the cross section of the existing canal it will not be possible to transport more than a 400 mg/l at full supply. Assuming an average sediment of 1·2 g/l in the river, then only the upper layers of the river-water must be taken off and the lower part containing an average of 830 mg/l must be led to the downstream side of the barrage by means of undersluices. The sinking material distribution from the bottom to the surface of the water being known, the desirable height above the floor of the skimming platform is fixed and also the discharge necessitated for the undersluicing is determined. Here the problem arises, to what extent the river will change its regime to be able to carry on this surplus of sediment (7 crores cub. feet annually). Aggradation of river beds occurs when a large portion of clear water is drawn by an irrigation canal leaving the sediment load, particularly the coarser particles, to be carried by the reduced flow. It is recommended to calculate with the given sediment theory the changes that will take place in the river beds before the link canals are constructed. By doing so, one can predict the consequences of running the link-canals with regard to extra damage by floods. Also, it can be foreseen whether the excluding of sediment from entering the canals is possible or not in the case where large discharges are taken off from the rivers. In other words, the technical feasibility of some of the proposed link-canals still has to be proved and the sediment charge theory may contribute in this respect.

Example 3. *Kalabagh-Jhelum link.*

If the Thal Multipurpose Project proposed by H. Vlugter will be constructed, the Kalabagh-Jhelum Link will be split up in a number of smaller canals which form the main drainage system of the northern part of the irrigated area in the Thal.

In that case the possibility exists to let the so-called Punja and Qaidabad drains scour out by the running water because the slope of the natural surface between the Mohajir Branch and the Jhelum is comparatively steep (1:3,000). An initial capacity of about 1000 Cs can be given and after a few years this capacity will have considerably increased as the following calculation shows :—

First Year :

Design :	A=297 sq. ft.	P=46·6 ft.
	R=6,4 ft.=1·95 m.	V=3,18 ft./Sec
	Q=944 Cs.	=0·97 m/Sec

The sediment concentration according to the simplified formula $G_s/G_w = V^4/2000$ will be 0,45 g/l.

The total transport per year will amount to about 8,000,000 cubic ft. which may cause an increase in width of 5,2 ft.

Second Year :

A=365 Sq. ft.	P=51,8 ft.
V=3,46 ft./Sec=1,06 m/Sec	R=7 ft.
Q=1,263 Cs.	=2,13 m

Then, the sediment transport will be 0,63 g/l or about 15,000,000 ft. in one year. Let the increase in depth be 3 ft. then the increase in width will be 5,2 ft.

Third Year ;

A=496 sq. ft.	P=60′	R=8,4 ft=2,46 m
V=3,86 ft./Sec=1,18 m/Sec		Q=1,914 Cs.

The sinking material transport amounts to 1,10 g/l which means a scour of 40,000,000 cubic ft. per year and an increase in width of 21 ft. can be the result.

Fourth Year ;

A=832 sq. ft.	P=81 ft.	R=10,3 ft.
V=4,42 ft./Sec=1,35 m/Sec	Q=3,680 Cs.	=3,15 m

Thus, after 3 years the capacity of this drain will be about 4 times the original one.

Example 4. *The Taunsa-Panjnad Link.*

It is the intention of the Irrigation Department to dig this link only to a small capacity (2,000 Cs.) letting it scour by the running water to a final capacity of 12000 cs.

The question to be answered is: which is most favourable cross section to be given initially and how much time will the scouring process take ?

The slope of the link in the first twenty miles will be 1:10,000 and in the remaining 20 miles 1:4,000.

Assuming for the second stretch of the canal a depth of 10 ft. a bed-width of 40 ft. and side slopes of 1:1·5 then : the cross section, A=550 sq. ft. the wetted perimeter, P=76′ the hydraulic radius, R=7,24′=2,20 m, the mean velocity, $V=KR^{2/3}\ S^{1/2}$, $K=25/E^{1/6}$, E=0,04 m, or in f.p.s. units $K=43/0{,}304^{1/3}=64{,}5$

Thus, 1,486/n=64,5 n=0,023. V=1,13 m/Sec=3,7 ft./Sec.
The discharge Q=2035 Cs. and the concentration of sinking material G_s/G_w $= V^4/800\ R^{4/3}=0{\cdot}7$ g/l

Now in case other hydraulic characteristics are given, *i.e.*,

D=14′ B=20′ with side slopes 1:1 then :

A=476 sq. ft.

P=56′

R=8,5′=2,69 m

V=1,29 m/Sec=4,23 ft./Sec.

Q=2014 Cs.=57·5 m^3/Sec.

G_s/G_w =0,91 g/l

It appears that the most favourable hydraulic section is the one which has the highest sediment carrying capacity. This is in accordance with the law of the conservation of energy for the less energy is spent on friction, the more will be available for the transportation of solid material. The first part of the Taunsa-Panjnad Link will have a slope of only 1:10,000.

Therefore, its silt transporting capacity will be rather low.

Assuming R=10′=3 m, then $V=43{\cdot}3^{\ 2/3}/\ 100=0{,}90$ m/Sec and the concentration of sinking material $G_s/G_w=V^4/800\ R^{4/3}$ =0,19g/1. The difference of 0,91 and 0,19 or approximately 0,7 g/1 will be the amount of particles with size bigger than 0,07 mm that will remove from the bed and the sides of the second part of the link. Therefore the scouring will be :—

0,7 ×57500 gram per sec

= 0,7 × 57,500 × 86,400 gram per day

= 0,7 ×57,5 × 86,4 ton per day

= 0,7 × 57,5 × 86,4/1, 4 m^3 per day

$=0,7 \times 57,5 \times 86,4 \times 30/1,4 m^3$ per 30 days

$=74,750$ m^3 for the first month

Apart from this quantity all the particles with a diameter less than 0,07 mm will be washed out.

Of course in the Thal desert the percentage of this silt is low, probably not exceeding 20%. Thus the total amount of material taken in suspension during 30 days will be 75,000+ 20% = about 90,000 m^3. Supposing further that the sand of the Thal desert does not contain particles bigger than 1 mm which could be carried along the bottom as bed-load, then about 300,000 cub. feet will be taken up along the 20 miles during the first month of operation. This will result in an enlargement of the cross section up to 30 sq. ft. As the original wetted perimeter was 56′ it may be expected that the depth of the canal will increase with about half a foot and the width with one foot during the first month of exploitation.

Example 5: Cut-offs.

Sometimes very small cut-offs are made with the intention to let them develop on their own by the running water. In such cases the experience mostly has not been satisfactory.

Assuming the river has a slope of 0,00010 and a hydraulic mean depth of 4 m (13 ft.)

Supposing a cut-off is constructed with a slope equal to 0,00030 and a hydraulic radius of R = 1 m only. The mean velocity of the river will be 1,25 m/Sec and that of the cut-off about 0,85 m/Sec.

The concentration of sinking material in the river is $G_s / G_w = V^{4} / 800\ S^{4/3} = 0{\cdot}5$ g/1.

The water flowing through the cut-off can carry a concentration $G_s / G_w = 0{\cdot}80^4 / 800.1^{4/3} = 0{\cdot}65$ g/1. Therefore no appreciable amount of scouring will occur.

However, when the cut-off is started with a hydraulic radius of 2 m, then the water velocity will amount to 1,35 m/Sec and the sediment concentration will be $1,35^4 / 1000 = 1,65$ g/1. The process of scouring in this case will proceed with 1,15 g/1 under the condition that the soil consists of fine sandy material.

Example 6. Bi- Tri- or Multi- furcations.

Suppose investigations in soil mechanics laboratory have indicated thete the banks of a canal in a certain soil are stable if its side slopes are constructed 1:2 over the upper 10 ft. below the water surface, 1:3 over the next 10 ft. depth and below that level 1:4, and further assuming that a depth is taken of 25 ft. and a bed width of 60 ft. then the hydraulic characteristics of a main irrigation canal with a mean velocity of 4 ft/Sec in such a soil are as follows :—

$$A = 3{,}500 \text{ sq. ft}$$
$$P = 210 \text{ ft.}$$
$$R = 16{,}67 \text{ ft.} = 5{,}08 \text{ m}$$
$$V = 4 \text{ ft./Sec} = 1{,}22 \text{ m/Sec.}$$
$$Q = 14{,}000 \text{ Cs.}$$
$$S = V^2 / C^2 \; R^{4/3} = 16/66^2 \times 16{,}67^{4/3} = 1/11800$$
$$= 0{,}000085.$$

In case the equivalent fall velocity of the sediment particles is $W = 2/10^2$ m/Sec and the wall roughness $E = 5/10^2$ m,
then, the concentration of sinking material transported by the running water will be $G_s / G_w = V^4 / 800 \; R^{4/3}$

(V and R in metric system units)

$$= 1{,}22^4 / 800.\ 5{,}08^{4/3} = 0.3 \text{ g/1}$$

Furthermore , $V^3 / R = 1{,}22^3 / 5{,}08 = 0{,}358$
When a bi -tri- or multi-furcation is to be made, then in accordance with the derived sinking material theory, each of the canals should be given the same value V^3 / R.

Thus, if for a branch with $R = 4$ m its mean velocity should be $V = (4.0{,}358)^{1/3} = 1{,}13$ m/Sec = 3.7 ft/Sec and if a distributary has a hydraulic radius of 2 m, then its mean velocity should be $V_{dist} = (2.0{,}358)^{1/3} = 0{,}89$ m/Sec = 2·9 ft./Sec.
and so on and so forth.

In conclusion it is stated that all the above given calculations of quantities of sediment are rough approximations.

Not taken into account was that the total suspended matter on an average moves slower than the water because its concentration near the bed where the water velocity is high is low and, on the contrary, in the surface layer the water velocity is high and the content of sediment low. On the other hand, more sinking material will be held in suspension if an appreciable amount of floating material is present. Both influences could of course be evaluated and more exact quantities determined.

The aim of this paper, however was to draw attention to the main factors governing the transport of debris by running water and to show how the sinking material theory could be applied in hydraulic engineering when designing canals or training works in rivers. In the immediate future in Pakistan a large percentage of the waters of the Rivers Jhelum and Chenab must be diverted for irrigation purposes. The above derived theory and the given examples may contribute, it is hoped, to solve the sediment problems which will result from the replacement works.

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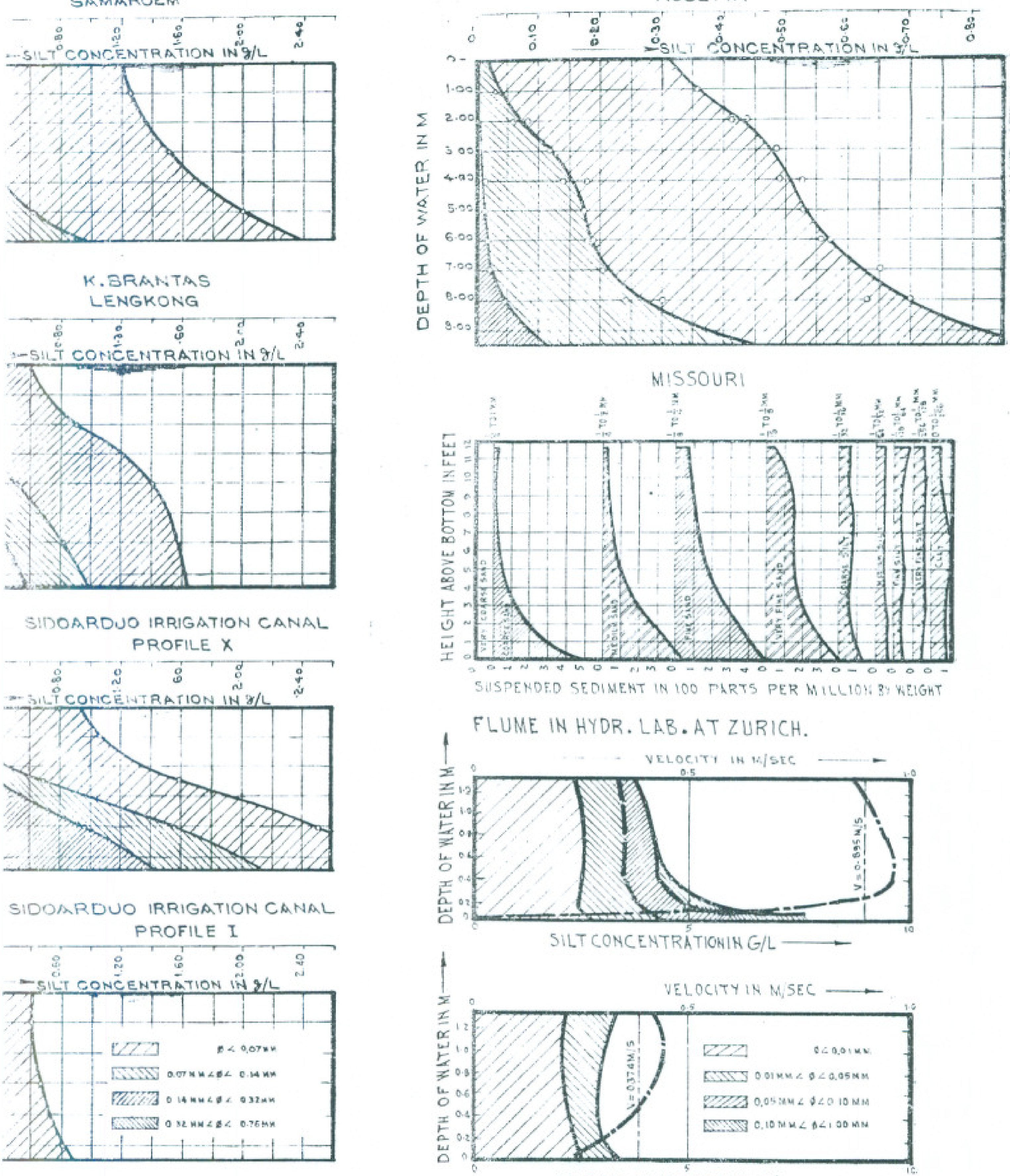

RAMS SHOWING. SILT DISTRIBUTION ACCORDING TO WATER DEPTH

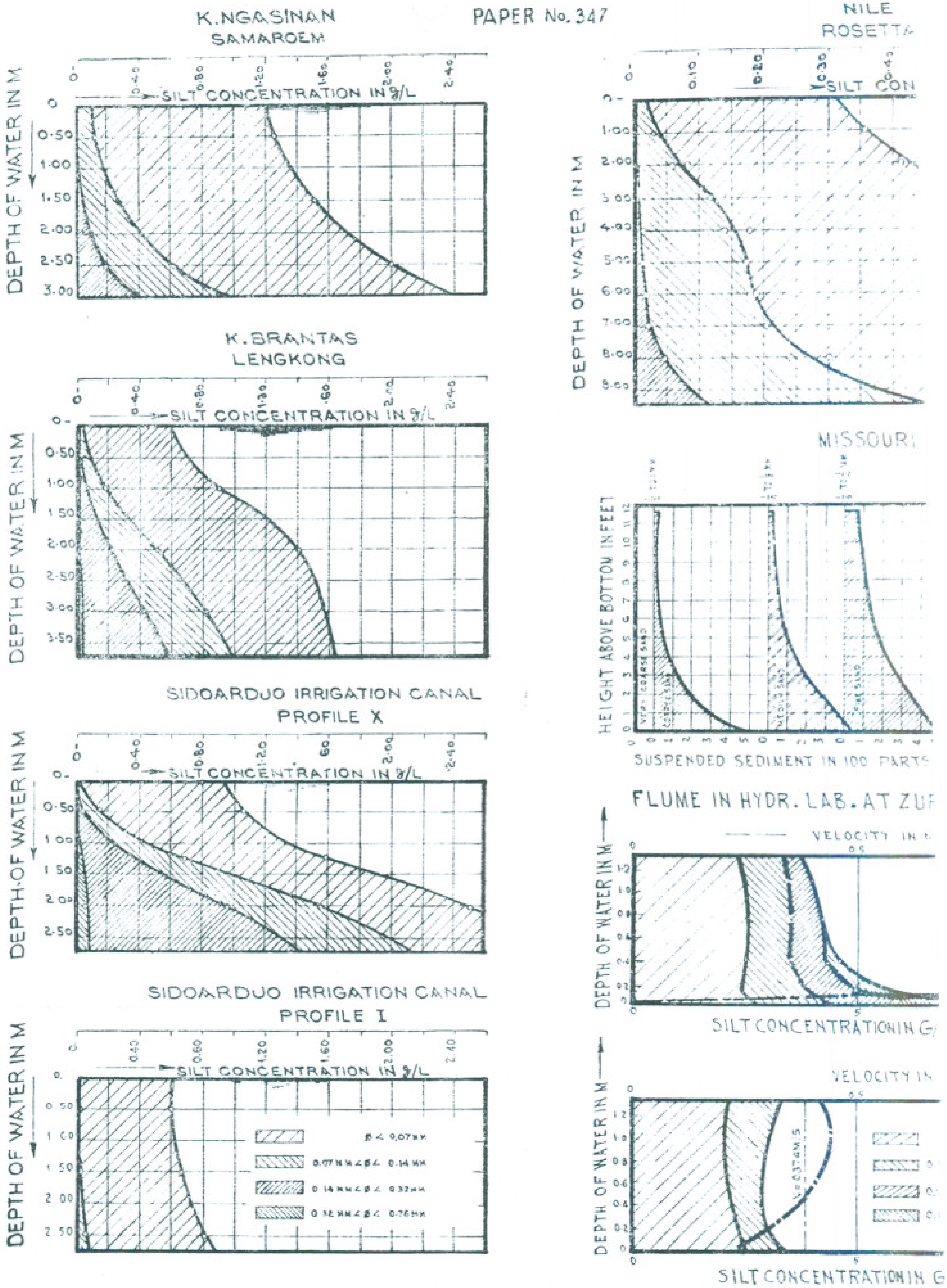

FIG 1 DIAGRAMS SHOWING. SILT DISTRIBUTION ACCORDING TO WATER DEP

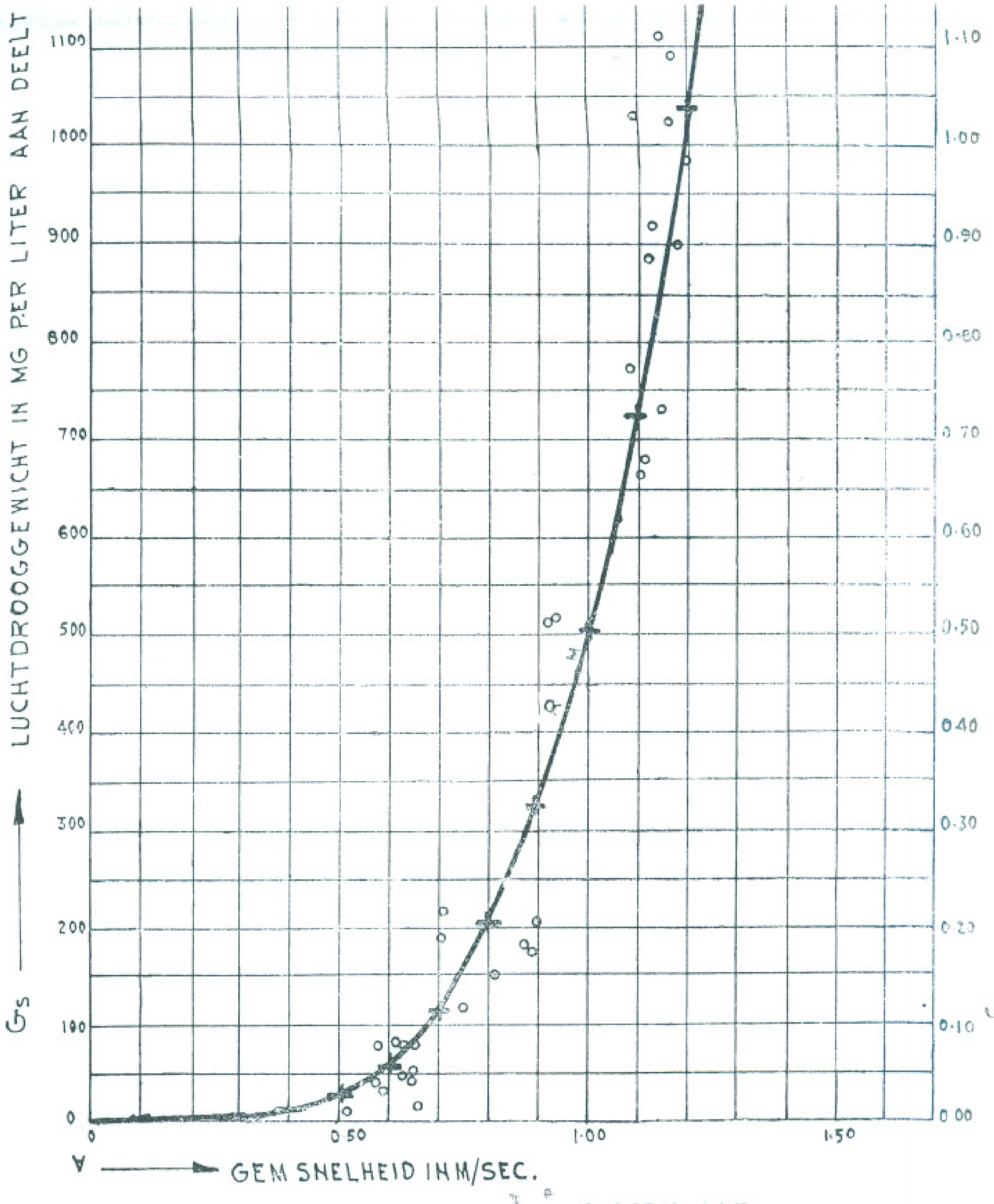

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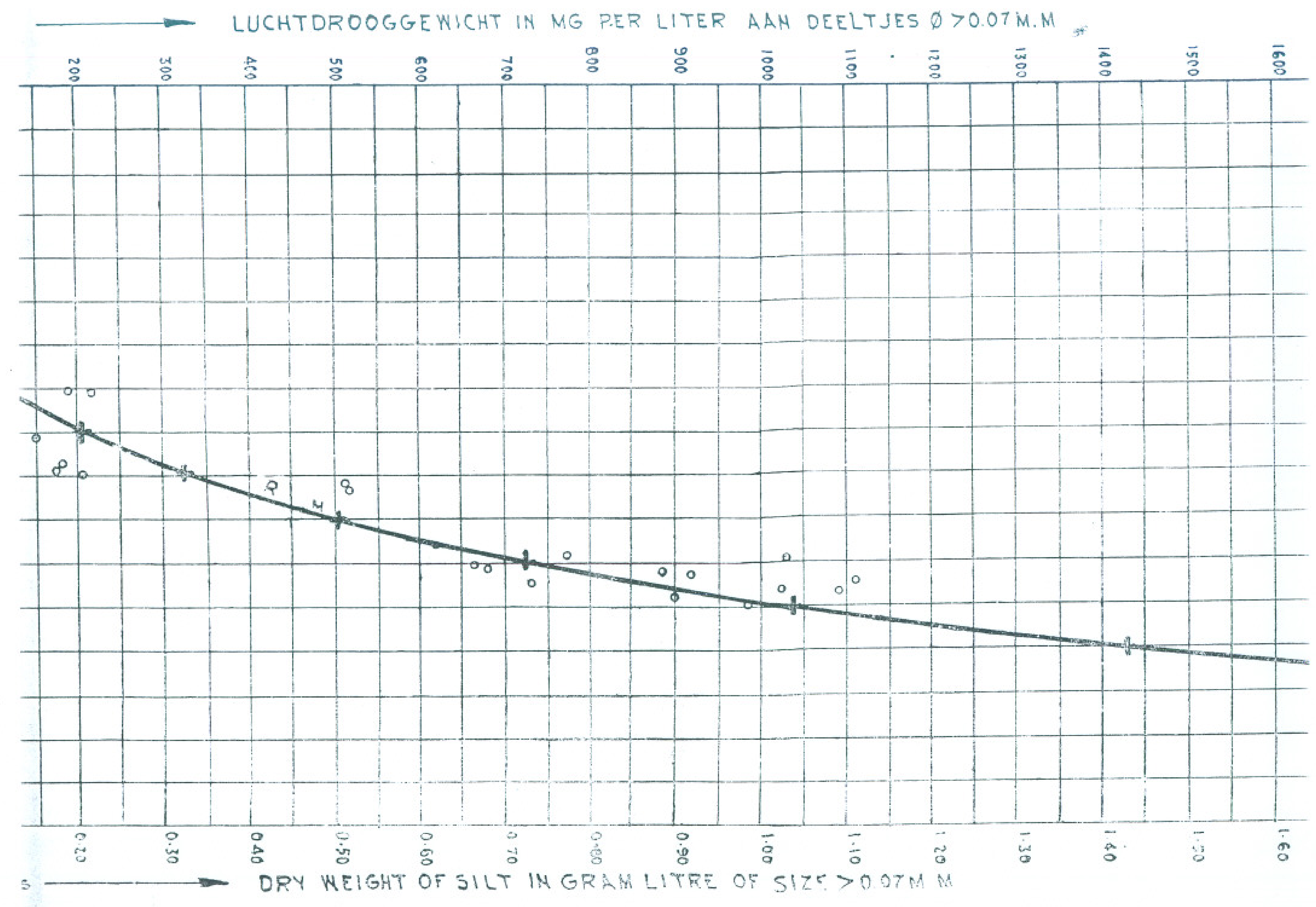
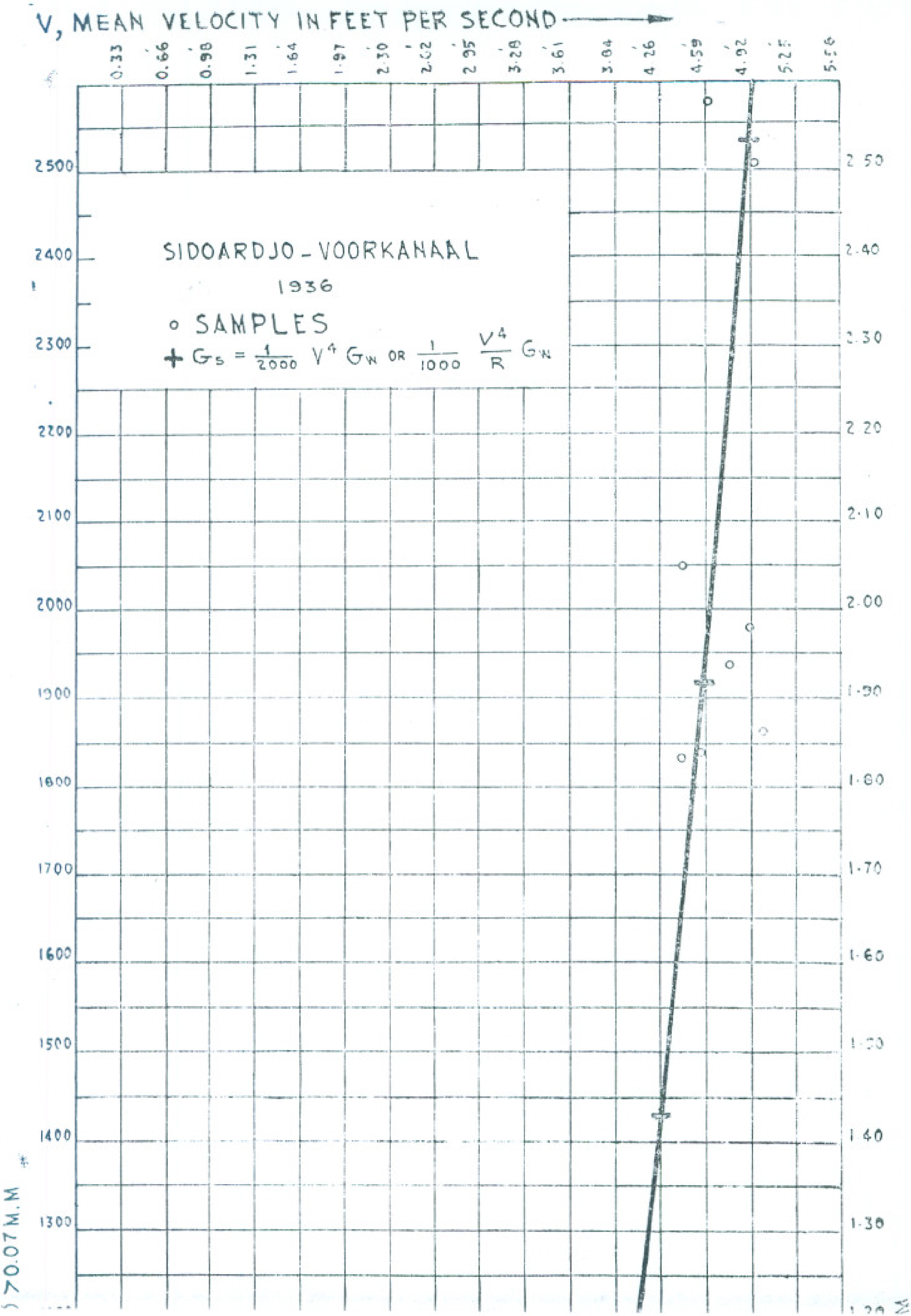
FIG. 2. GRAPH SHOWING RELATION BETWEEN SINKING MATERIAL AND VELOCITY.



LUCHTDROOGGEWICHT IN MG PER LITER AAN DEELTJES Ø >0.07 M.M
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
0.20
0.30
0.40
0.50
0.60
0.70
0.80
0.90
1.00
1.10
1.20
1.30
1.40
1.50
1.60
DRY WEIGHT OF SILT IN GRAM LITRE OF SIZE >0.07 M M



V, MEAN VELOCITY IN FEET PER SECOND
0.33
0.66
0.98
1.31
1.64
1.97
2.30
2.62
2.95
3.28
3.61
3.94
4.26
4.59
4.92
5.25
5.58
SIDOARDJO - VOORKANAAL
1936
o SAMPLES
+ $G_s = \frac{1}{2000} V^4 G_w$ OR $\frac{1}{1000} \frac{V^4}{R} G_w$
2500
2400
2300
2200
2100
2000
1900
1800
1700
1600
1500
1400
1300
2.50
2.40
2.30
2.20
2.10
2.00
1.90
1.80
1.70
1.60
1.50
1.40
1.30
1.20
70.07 M.M