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Analysis of the vertical distribution of high sediment concentrations in the Yellow River and studies of methods of observation

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ABSTRACT Based on analyses of field data, it is demonstrated that the distribution of sediment at high concentrations in the Yellow River is uniform. This is primarily due to three causes; firstly, the effect of the initial conditions of sediment yield in the basin, secondly, the influence of the ultimate tangential stress of the fluid and, thirdly, the structure of the sediment mass. It has been found that theoretical formulae for determining the vertical distribution of sediment concentration, derived for low silt contents, are not applicable to conditions of hyperconcentration. Requirements for the methods and instruments used in measuring hyperconcentrations of sediment should be different from those for the measurement of low sediment content.

CHARACTERISTICS OF SEDIMENT DISTRIBUTION

During the flood season, the flow of the Yellow River and its tributaries in the middle reaches generally exhibit hyperconcentrations of suspended sediment. Based on observations at several of the gauging stations in this area (Fig.1), the following analysis was undertaken.

The mechanism of sediment movement in hyperconcentrated flows is different from that operating at low sediment content. The vertical distribution of sediment concentration therefore differs greatly in

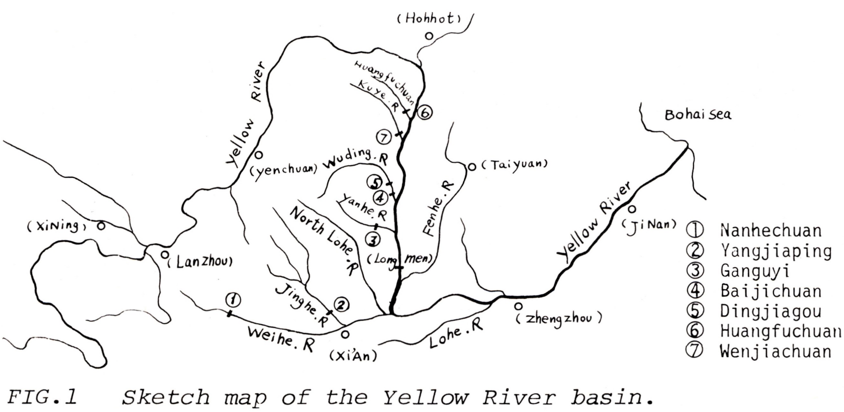

FIG.1 Sketch map of the Yellow River basin.

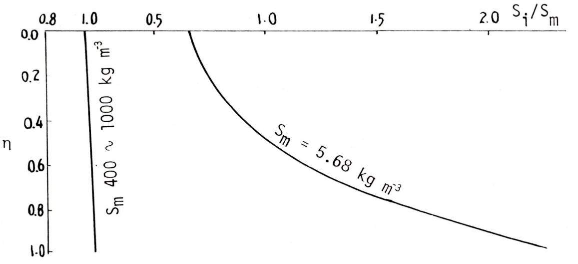

FIG.2 Vertical variation of the ratio S_i/S_m for high and low concentrations of sediment in the Wuding River at Dingjiagou.

character. Typical vertical distributions of the ratio of sediment concentration at a specific point in the cross section to the average concentration for the vertical passing through that point (S_i/S_m) are shown in Fig.2. In the case of hyperconcentration of sediment (400-1000 kg m^{-3}), the distribution assumes a straight line, with a gradient in general less than 0.1. For a flow with low silt content (5.68 kg m^{-3}), the distribution is, however, curvilinear, with an average gradient larger than unity. The effects of grain size may be demonstrated by considering the distribution of sediment concentration in the vertical in the Weihe (fine-grained sediment) and Wuding Rivers (somewhat coarser particles) (Fig.3). The results

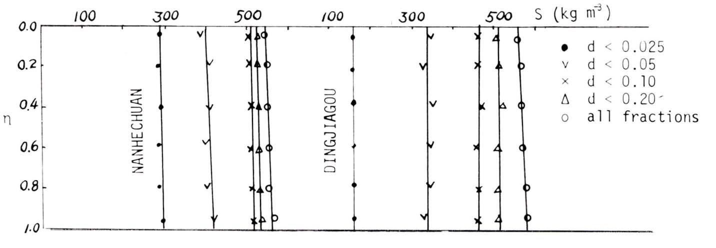

FIG.3 Distribution of concentration of sediment of various grain sizes along verticals at Nanhechuan and Dingjiagou.

of analysis of data collected from 187 verticals at seven gauging stations on six of the main tributaries of the Yellow River, to determine the distribution of the relative concentration of sediment in the vertical are shown in Table 1.

In the case of hyperconcentrations, the vertical distribution of sediment concentration and grain size is essentially uniform (Fig.3). In dealing with the transport of solid-liquid flow through slurry pipelines, Wasp *et al.* (1977) indicated that the criterion for uniform suspension is $S/S_a \geqslant 0.8$, where S/S_a is equivalent to the ratio of concentration of suspended sediment at the water surface and that at the river bottom. With hyperconcentrations of sediment, all values of the ratio S/S_m for different sizes of sediment measured at these stations lie above 0.8 or, at least, close to 0.8 (Huangfuchuan and Wenjiachuan). Thus, the distribution may be

TABLE 1 Vertical distribution of sediment concentration at six gauging stations on the Yellow River

River	*Station*	S_i/S_m *Surface*	*0.2*	*0.6*	*0.8*	*Bottom*
Weihe R.	*Nanhechuan*	*0.979*	*0.998*	*1.003*	*1.005*	*1.017*
Jinghe R.	*Yangjiaping*	*0.991*	*0.995*	*1.002*	*1.006*	*1.014*
Yanshui R.	*Ganguyi*	*0.990*	*1.004*	*1.003*	*0.997*	*1.000*
Wuding R.	*Baijiachuan*	*0.965*	*0.990*	*0.996*	*1.030*	*1.018*
Wuding R.	*Dingjiagou*	*0.962*	*0.977*	*1.012*	*1.019*	*1.042*
Huangfuchuan	*Huangfuchuan*	*0.884*	*0.972*	*1.007*	*1.033*	*1.119*
Kuye R.	*Wenjiachuan*	*0.884*	*0.972*	*1.007*	*1.033*	*1.119*

viewed as uniform.

The transverse distribution is also uniform at high sediment concentrations. Based on analyses of observed data, it has been found that the range of variation of the ratio of mean sediment concentration in a particular vertical to that in the entire cross section is 0.95-1.06. At concentrations higher than 10 kg m^{-3}, the error involved in assuming that the mean sediment concentration along an individual vertical is representative of the average value for the entire section will not exceed ±5-10%; for concentrations above 100 kg m^{-3}, the maximum error will be less than ±5%.

In short, in flows with hyperconcentrations of sediment, the variation of sediment content both in the vertical and transverse directions shows a uniform distribution. This basic feature applies to both the size and the concentration of solid matter carried. Owing to the different compositions of sediment in different rivers, the degree of uniformity in the distribution differs.

BASIC CAUSES OF THE UNIFORM DISTRIBUTION OF HYPERCONCENTRATED SEDIMENT

Effect of initial conditions of sediment yield

The middle reaches of the Yellow River lie largely in the loess region where the soil is fine-grained. According to statistics derived from data collected at Nanhechuan and Dingjiagou, the gravimetric percentage of fine particles (<0.05 mm) is over 75% and 50% respectively for 80% of the measurements taken. Storm rainfall in this area is usually localized and of high intensity, the slope gradients are steep and the slopes and gullies have been severely eroded. According to observations made on runoff plots at the Zizhou Runoff Experimental Station on the Wuding River, sediment concentrations in slope runoff are mostly over 400-1000 kg m^{-3}. Sediment delivery from the tributaries is very efficient and lies very close to the loss of soil from medium or small basins. These features show that the initial conditions are favourable for the uniform distribution of highly concentrated sediment in the river.

Ultimate tangential stress of the fluid

In flows with hyperconcentrations of sediment, the fluid is usually a non-Newtonian body. The ultimate tangential stress (τ_0) increases with an increase in sediment concentration and is dependent on the composition of the sediment. Through tests on samples taken from the Weihe and N. Luohe Rivers, the Northwestern Hydraulic Research Institute (Zhang *et al.*, 1980) obtained the following relationships: when $S > S_k$,

$$\tau_0 = 2.88\beta^{2.23}(S \times 10^{-3})^{4.33} \quad (1)$$

when $S < S_k$,

$$\tau_0 = 0.125\beta(S \times 10^{-3})^{1.732} \quad (2)$$

$$S_k = 282\beta^{-0.462} \quad (3)$$

where: β = fraction of particles finer than 0.025 mm in total sediment load.

According to the work of Shischenko (1957) the ultimate tangential stress of a fluid in which the sediment is in the limiting state of equilibrium is expressed thus:

$$\tau_0 = k\, d_0(\gamma_s - \gamma_m)/6 \quad (4)$$

in which
d_0 = limiting size of particle remaining in suspension in the fluid;
γ_s, γ_m = density of sediment and silt-laden water respectively;
k = coefficient related to grain size.
Research workers on the Yellow River (Qian *et al.*, 1980) used d_{95} instead of d_0 in their experiments and obtained:

$$d_0 = 5.7\, \tau_0/(\gamma_s - \gamma_m) \quad (5)$$

The above formula was employed to analyse data from the Nanhechuan and Dingjiagou measuring stations, giving relationships between d_0/d_{50} and d_0/d_{95} and S as shown in Fig.4. For concentrations of 200-400 kg m^{-3}, d_0 is generally larger than d_{50} and for concentrations of 500-800 kg m^{-3}, d_0 is in general larger than d_{95}, and almost all the sediment will remain in suspension uniformly, even in the state of rest. This is the principal condition for the formation and maintenance of uniform distributions of sediment of hyperconcentration.

Influence of the structure of the sediment mass

It has been shown by a large number of observations that in general particles larger than d_0 also exhibit uniform distributions. This is chiefly due to the interaction between grains, which plays a predominant role in place of the force of gravity. Assuming that the particles are spherical, the distance between grains is dependent on the sediment concentration:

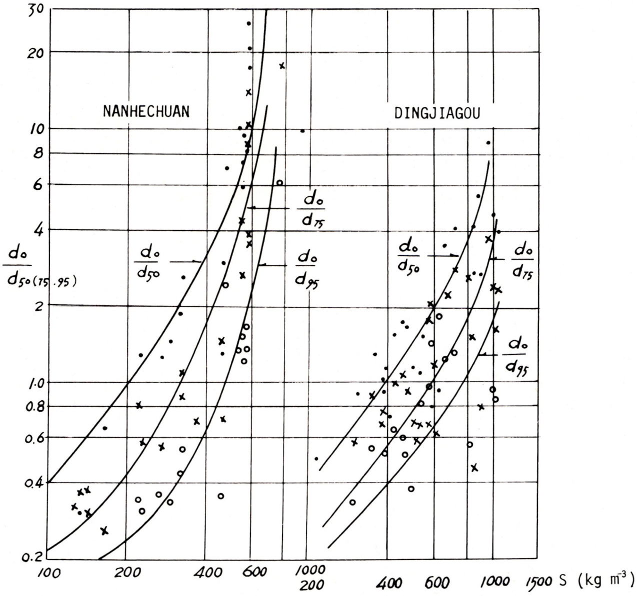

FIG.4 Relationships between S and d_0/d_{50}, d_0/d_{75} *and* d_0/d_{95} *for data obtained from Nanhechuan and Dingjiagou.*

$$L/d = S_V^{-1/3} - 1 \qquad (6)$$

in which
L = distance between grains;
d = grain size;
S_V = volumetric sediment concentration.

For concentrations higher than 300 kg m^{-3}, L < d, and the finer particles are highly dispersive and possess strong physicochemical surface activity. Densely concentrated, the finer particles tend to form a structure with a certain rigidity, so that the tendency for the coarsest particles in the mass to segregate and deposit is weakened.

According to an analysis of data from Nanhechuan and Dingjiagou, at concentrations higher than 200 kg m^{-3} over 34.5% of the verticals show uniform distribution of all the sediment, the settling velocity being zero. This suggests that the settling velocity of the small portion of sediment coarser than d_O diminishes appreciably in the new medium. After the formation of the structural mass, the effect of gravity tends to disappear and this is the chief reason why the fractions coarser than d_O are also uniformly distributed.

Taken together, the initial conditions of sediment yield from the basin, the ultimate tangential stress of the fluid and the structure of the sediment mass are the three basic factors, indivisible from one another, leading to the formation and maintenance of a uniform distribution of sediment, both coarse as well as fine.

STUDIES OF FORMULAE FOR COMPUTING THE VERTICAL DISTRIBUTION OF SEDIMENT

In the case of low concentrations of sediment, the movement of the suspended particles is governed by the force of gravity and the dispersing effect of turbulence. The basic formula is derived from the theory of dispersion:

$$S\omega + \varepsilon_s . dS/dy = 0 \tag{7}$$

Supposing that the dispersion coefficient ε_s remains constant along a vertical, and is equal to the coefficient of momentum exchange ε_m, the formula for computing the distribution of low sediment concentration in a vertical can be derived by applying the formula for logarithmic distribution of velocity of flow :

$$S/S_a = |(H - y)(a)/(y)(H - a)|^z \tag{8}$$

in which z = the index of dispersion which equals $\omega/\beta K\, u_*$.

The index z is obtained by analysing observed data in the following way. The observed values S/S_a are plotted as abscissae and the values of $(H - y)(a)/(y)(H - a)$ as ordinates, on logarithmic paper to obtain z_{act}. The values of z_{th} (theoretical) are computed from observed values of the Karman constant K, the dynamic velocity u_*, and the settling velocity ω (modified for the case of muddy water). The relationship between z_{act} and z_{th} is shown in Fig.5.

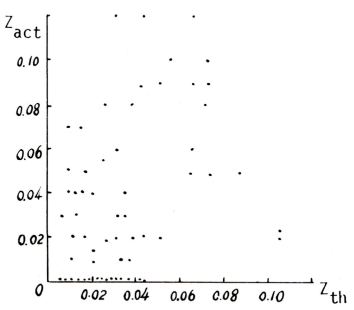

FIG.5 The z_{act}/z_{th} relationship.

It can be seen that in the main a linear relationship does not exist. This proves that under conditions of hyperconcentration of sediment, owing to the weakening or even vanishing of the gravitational effect on sediment movement, the exchange of water and the aggregated mass of sediment, though present, is no longer decisive to the spatial distribution of sediment. This is the basic reason why the formula based on the theory of dispersion is not applicable to hyperconcentrated sediment.

At the present level of our knowledge, an empirical linear equation is used to express the distribution of high concentrations of sediment in the vertical:

$$S = S_{0.0}(1 + k\eta) \tag{9}$$

in which
k = slope ratio of the distribution curve, which equals $(S_{1.0} - S_{0.0})/S_{0.0}$;
$S_{0.0}$, $S_{1.0}$ = sediment concentration at the surface and river bottom respectively.

The value of k varies for different areas. In regions yielding fine sediment, the distribution curve is essentially a vertical line, and k may be taken as zero. In regions producing coarse sediment, the relation between k and sediment concentration is shown in Fig.6. The value of k is generally smaller than 0.1.

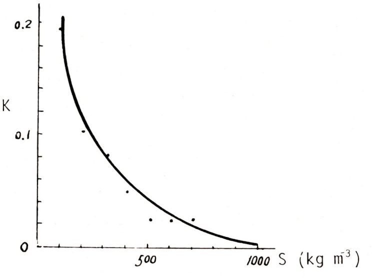

FIG.6 The k/S relationship.

PROBLEMS IN SEDIMENT MEASUREMENT

(a) The measurement of variations in tangential stress in fluids with high concentrations of sediment is of considerable significance. There is much variation in the rheological behaviour of flow in rivers with hyperconcentrations of sediment, as seen in Fig.7. Measurements should therefore be taken at the main gauging stations until sufficient data have been gathered in a comprehensive way, to satisfy the need of establishing an overall rheological equation of adequate precision for practical purposes.

(b) At gauging stations on the tributaries it is only necessary to measure "single" values of sediment concentration during times of high silt content, and it is possible to follow closely the changes in sediment content. Observations of total sediment flux over the entire section are not generally required, thanks to the following:

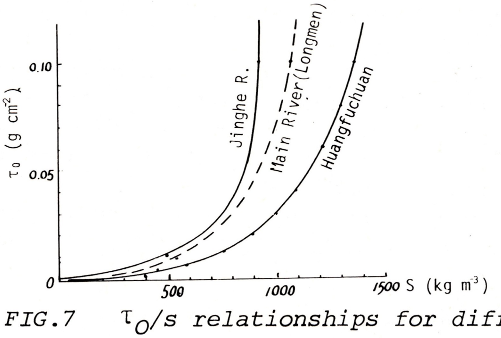

FIG.7 τ_0/s relationships for different areas.

(i) The weighted velocity of flow is not necessary for computing average sediment concentration in a vertical. The error thus introduced will not be appreciable. Take for instance an estimate using the five-point method.

When weighted velocity of flow is taken into consideration, the mean sediment concentration in a vertical is given by the expression:

$$S_m = (V_{0.0}S_{0.0}+3V_{0.2}S_{0.2}+3V_{0.6}S_{0.6}+2V_{0.8}S_{0.8}+V_{1.0}S_{1.0})/10V_m$$

Inserting equation (9) into the foregoing expression, we obtain after rearranging:

$$S_m = S_{0.0} + kS_{0.0}(0.6V_{0.2} + 1.8V_{0.6} + 1.6V_{0.8} + V_{1.0})/10V_m \quad (10)$$

Take for instance the Dingjiagou station. It was determined from the experimental data that:

$V_{0.0} = 1.25V_m$; $V_{0.2} = 1.18V_m$; $V_{0.6} = 0.97V_m$;

$V_{0.8} = 0.816V_m$; $V_{1.0} = 0.615V_m$.

By inserting into equation (10) and rearranging, we obtain:

$$S_m = S_{0.0}(1 + 0.438k)$$

Not taking the weighted velocity of flow into consideration, the mean sediment concentration in a vertical is expressed by:

$$S'_m = S_{0.0}(1 + 0.5k) \quad (11)$$

For k = 0.1, the relative error when neglecting the weighted velocity of flow is only $(S_m - S'_m)/S_m = -0.59\%$.

(ii) Owing to the fact that the distribution in the transverse direction is also uniform, the method of measuring a "single" value of sediment concentration can be used to represent the average concentration over the entire section, after being substantiated by experimentation. Definite evidence is provided by the relationship between the concentration measured at a single point and the average for the entire section. The relationship evidences a uniform 45° slope for data from all gauging stations on the tributaries of the middle reaches of the Yellow River. For the same reason, only single samples are necessary for obtaining the size distribution.

(iii) The one-point method may be used and samples should be taken at 0.5 depth, the point where the concentration is equal to the average value in the vertical. When the single sample is taken at the water surface, a correction should be introduced, in accordance with the k/S relationship for the area concerned.

(iv) The effect of pulsation is very slight under conditions of hyperconcentration. The relative square error is less than ±1.5% when the concentration is above 100 kg m^{-3}, and less than ±1.0% for concentrations exceeding 400 kg m^{-3}. Measurements at Wubao and the Sanmenxia station, both on the main river, as well

TABLE 2 The effect of the K_v value on the data obtained

S (kg m^{-3})	436	442	434	267	129	59.1
K_v	0.33	0.43	0.59	0.61	0.82	0.94
Relative error of S (%)	-0.2	0.2	-1.8	0.7	0	-4.1
D_{50} (mm):						
time-integration	0.036	0.038	0.037	0.050	0.026	0.033
horizontal sampler	0.037	0.039	0.036	0.052	0.025	0.034
Absolute error (%) of percentage by weight of fractions finer than a given size:						
0.005	2.7	-0.7	-1.9	-0.3	-1.3	1.4
0.010	3.2	-0.4	-0.8	-0.4	-0.9	1.7
0.025	3.8	-1.0	-1.8	-1.1	-1.5	1.3
0.050	4.8	0.9	-1.4	0.3	-0.5	1.1
0.100	1.9	-0.5	3.2	-0.5	-0.3	0
0.250	0	-2.2	-0.6	-1.0	0.4	0.3

as at other stations, have shown that a deviation of only $\pm 3.4/n^{0.5}\%$ was found when comparing a single instantaneous value of sediment concentration measured with a horizontal zampler with the mean value of n successive measurements. For the tributaries, it is $\pm 2.2/n^{0.5}\%$, as shown by experiments at the Qingyang gauging station and other sites. A strict 45° line relationship exists when comparing measurements of sediment concentration and size distribution obtained using a horizontal sampler and those provided by a time-integrating sampler. Hence, the same precision may be achieved by using horizontal samplers, which are simple in construction and easy to handle, in place of a time-integrating sampler, in hyperconcentrated flows. The requirements for selecting the instrument and the number of replicate measurements should not be the same for high and low sediment content.

(v) When using time-integrating samplers, it is generally a requirement that the inlet velocity should be the same as the natural flow velocity. The ratio between the two (K_V) should lie within the range of 0.9-1.1. Owing to the increase in viscosity for hyperconcentrated flows, the value of K_V diminishes appreciably. However, because the sediment is distributed uniformly, it can be seen from Table 2 that the effect is insignificant, because the error in measured concentration and size distribution is negligible. It is therefore considered unnecessary to insist that $K_V \simeq 1.0$, a condition which is rather difficult to achieve.

To summarize, more items may be specified for the measuring of sediment, but the methods of observation can be greatly simplified and the requirements for the selection of instruments may be less strict, in view of the distribution characteristics of high concentrations of sediment.

REFERENCES

Wasp, E.J. *et al.* (1977) *Solid-Liquid Flow Slurry Pipeline Transportation*. Trans-Tech. Publication, Germany.

Zhang Hao *et al.* (1980) Settling of sediment and the resistance to flow at hyperconcentrations. *Proc. Int. Symp. River Sedimentation, Beijing*.

Shischenko, R.I. (1957) *Hydraulics of Slurry* (translated from Russian).

Qian Yiying *et al.* (1980) Basic characteristics of flow with hyperconcentration of sediment. *Proc. Int. Symp. River Sedimentation, Beijing*.