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SEDIMENT TRANSPORT AT VERY HIGH CONCENTRATIONS AND ITS MOVEMENT BEHAVIOR

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In the Yellow River, the annual average sediment discharge and the annual average sediment concentration are the highest in the world. The measured maximum concentration approaches 1600 kg/m^3 in its tributary. The mechanisms of sediment movement are much different between very high concentrations and the general concentration. For the case of hyperconcentration, the decisive condition for the suspension of sediment particles is the Bingham ultimate shear stress (for Model I), or the intergranular dispersive stress (for Model II), but it is no longer the vertical turbulent intensity of the flow. The theoretical equations of vertical suspended sediment concentration such as the Rouse equation derived from low sediment concentrations are no longer applicable.

GENERAL

The loess plateau, which consists of 60-70% silt with a very uniform distribution, is extensively distributed in north China and the south part of northeastern China. The Yellow River passes through this region. By virtue of primary statistics, the amount of average erosion is approximately 3700 metric tons per square kilometer per year in the middle part of the Yellow River catchment. This value is 27.5 times the average erosion modulus for the world (134 tons per square kilometer per year), because the loess is by nature prone to erosion.

The measured data shows that there are 40 rivers in which the maximum concentration of sediment is greater than 1000kg/m^3 for the great river in China. The annual average sediment discharge of 1640 million tons and the annual average sediment concentration of 37.6kg/m^3 in the Yellow River are both the highest in the world. In fact, the sediment concentration in some tributaries is much greater than in the main stream in the Yellow River catchment. For example, the annual average concentration approaches 600kg/m^3, and the measured maximum concentration approaches 1600kg/m^3 in the Zuli River in Gansu province. In other words, the sediment volume occupies 60% of the water-silt volume. The local people say that “Every cup of water is half sediment”.

What is the mechanism and behaviors of sediment flow movement at very high concentrations? This is just the topic which will be dealt with in this paper.

MEASURED VERTICAL DISTRIBUTION OF HIGH SEDIMENT CONCENTRATION

An appreciable characteristic of the vertical distribution for high sediment concentration is that it is very uniform. Figure 1 is the measured vertical distribution of high sediment concentration with different grain sizes at Nanhechuan and Dingjiagou gauging station.

In short, in the flow with hyperconcentration of sediment, the variation of sediment concentration in the vertical direction shows a very uniform distribution. This characteristic applies to both the size and the concentration of sediment carried by flow. Owing to the different compositions of sediment in different rivers, the degree of the uniformity in the distribution differs. These sediment concentration characteristcs are very different from those at low concentrations where concentration increases from the water surface to the bottom.

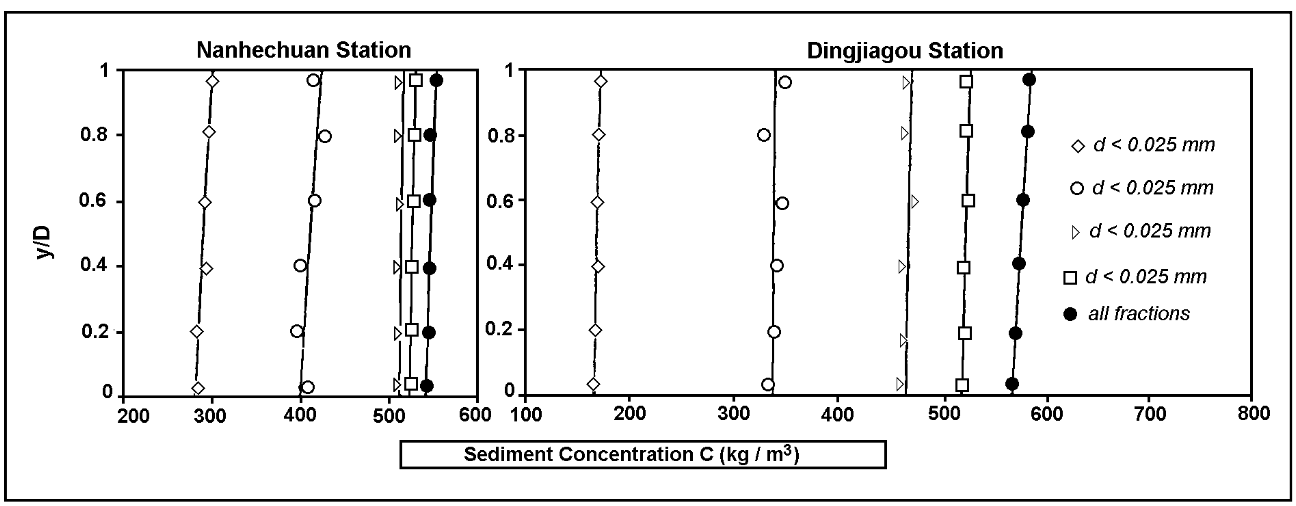

Figure 1. Vertical distribution of high sediment concentration with different grain sizes at Nanhechuan and Dingjiagou gauging station.

EXTREME MODEL I AND ITS MECHANISM OF SEDIMENT MOVEMENT WITH HYPERCONCENTRATIONS

High sediment concentration flow may be, in principle, classified into two extreme models due to the different composition of materials for convenience in order to discuss the mechanism of sediment transport.

a) Extreme model I of sediment movement with hyperconcentration

Model I *is a high sediment concentration flow in which the sediment particles mainly consist of fine silt and clay.*

This type of high sediment concentration flow is a non-Newtonian fluid which in general is realized as a Bingham fluid. The Bingham ultimate shear stress plays a decisive role. Along with the increment of the sediment concentration, a flocculent structure between the sediment particles soon forms, and the intergranular cohesion increases. During the settlement of the sediment particles the whole grains are no longer segregated into different grain sizes, but in its entirety the sediment settles very slowly at the border between clear water and muddy water, and the settling velocity is several hundred or even a thousand times smaller than the settling velocity of the individual grain. In fact the entire flow becomes a uniform mud flow for that time. For the different grain sizes, the critical sediment concentration for occurrence of uniform mud flow are different. The grains are finer, the critical sediment concentration is smaller, and vice versa. According to the experimental results of Z.H. Wan et al. (1979), for the sediment sample in which $d_{50} = 0.0015$ mm, and 85% of the grains are less that 0.01 mm, when the sediment concentration approaches 90 kg/m^3, the uniform mud flow can form.

b) Mechanisms of the sediment transport for Model I

In high sediment concentration flow, the effect of turbulent fluctuation velocity on suspension of sediment particles weakens and even disappears. How then are the sediment particles kept in suspension? In the Bingham fluid of Model I, the Bingham ultimate shear stress (τ_B) increases with the increment of sediment concentration and depends upon the composition of the sediment. Through the tests on samples taken from the Weihe and Beiluohe rivers the following relations are obtained:

for $C > C_f$

$$\tau_B = 2.88\beta^{2.23}\left(C \cdot 10^{-3}\right)^{4.33} \tag{1}$$

for $C < C_f$

$$\tau_B = 0.125\beta\left(C \cdot 10^{-3}\right)^{1.732} \tag{2}$$

$$C_f = 282\beta^{-0.426} \tag{3}$$

where

τ_B is the Bingham ultimate shear stress;

β is the fraction of particles finer than 0.025 mm in total sediment load;

C_f is the reference sediment concentration.

According to Shiseheko (1957), the Bingham ultimate shear stress of a fluid in which the sediment is in the limiting state of equilibrium can be expressed as follows:

$$\tau_B = \frac{1}{6}\lambda d_c(\rho_s - \rho_m)g \tag{4}$$

in which

d_c is the critical size of the sediment particle keeping in suspension in the fluid;

λ is a coefficient related to grain size;

ρ_s, ρ_m are the density of sediment grains and the mixture of the silt-laden water, respectively.

According to Wan et al. (1979), $\lambda \approx 1.05$. Then equation (4) can he rewritten as:

$$d_c = 5.714\frac{\tau_B}{g(\rho_s - \rho_m)} \tag{5}$$

Therefore, when the maximum grain, say d_{95},is less than the d_c of equation (5), then all particles could stay in suspension and in movement so long as the flow has the adequate slope.

By the analysis of Zhao et al. (1982) for the measured data at the Nanhecuan and Dingjiagou stations, when the sediment concentration approached approximately 500 kg/m^3 and 800 kg/m^3, respectively, then d_c is in general larger than d_{95}; in other words, almost all of the sediment particles will stay in suspension with a uniform concentration.

EXTREME MODEL II AND ITS MECHANISMS OF SEDIMENT MOVEMENT WITH HYPERCONCENTRATIONS

Model II *is a high sediment concentration flow in which the sediment particles mainly consist of fine sand and larger grains.*

In this case without the finer grains as the basic framework, the flow keeps to the behavior of a Newtonian fluid when the sediment concentration is not very high. If the sediment concentration is very high, the Bingham ultimate shear stress can occur, but its value is in general smaller according to Chien's (1983) experimental results. Although the settling velocity of sediment grains decreases with the increment of sediment concentration, the degree of the decrease is smaller than in Model I. The different grain sizes are segregated during the settlement process. The flow belongs to the two-phase silt-laden flow. Along with the increment of the sediment concentration, the turbulent intensity weakens continuously, and the intergranular dispersive stress (Bagnold, 1954), which occurs due to the intergranular relative shear movement, plays a more and more important role. Finally the turbulent flow becomes laminar, the weight of the all sediment particles is supported by the dispersive stress between grains, and the vertical sediment concentration distribution becomes very uniform.

According to Bagnold's flume experiments with grain size d = 1.36 mm, when the volumetric concentration of sediment, C, approaches 30%, the turbulent phenomenon weakens. Meanwhile, the vertical distribution of the sediment concentration tends to become uniform. After C = 35% the turbulent phenomenon disappears; the result is that the sediment with uniform distribution is transported by laminar flow. The cohesion of the flow increases appreciably and flow velocity decreases gradually. And when $C \approx 60\%$, the intergranular distances are too small to keep the grains in movement, and the whole silt-laden flow stops as if it were "freezing".

PRACTICAL MOVEMENT MODEL IN STREAMS OF NORTHWEST CHINA

The behavior of high sediment concentration flow in Northwest China lies between Model I and Model II discussed above. There are very fine grains as the framework, as well as a certain quantity of coarse sediment particles in the flow. In more northerly rivers, e.g. the Huangfuchuan River, Wudinghe River etc., the concentration of the coarse grains is greater. When the concentration of sediment increases to a certain value, the fine grains form a flocculent structure, and form a uniform mud flow with the water, in which the velocity of the fine grains tend to zero and the velocities of the coarse grains is much lower than their velocities in clear water, so the sediment concentration tends to be uniform.

According to the analysis of measured data from the Nanhecuan and Dingjiagou stations by Zhao et al.(1982), when the sediment concentration is just over 200 kg/m^3, the fine grains tend to form a flocculent structure, and the tendency of segregation and deposition is weakened obviously for the coarser grains. Along with the increment of sediment concentration, more and more coarse grains take part in the flocculent structure and became a part of the uniform mud flow, and the vertical distribution of sediment concentration becomes more and more uniform. Finally the whole flow may become the uniform mud flow when the sediment concentration exceeds a critical value for some rivers leading to the phenomen of "mud rivers"in some tributaries of the Yellow River.

"MUD RIVER" - A SPECIAL SEDIMENT PHENOMENON IN RIVERS OF NORTHWEST CHINA

When the sediment concentration exceeds a certain extreme value, and the flood peak suddenly drops down, the velocity of flow decreases quickly, and the flow of the entire river reach sometimes stops moving and becomes still for a while. This special stopping phenomenon of a river reaches, which is caused by very high sediment concentration, is called "*mud river*" by local people in Northwest China.

An example of the "*mud river*" phenomenon was observed at Lijiahe hydrological station of Xiaolihe River on 17th June, 1963. The maximum sediment concentration was 1220 kg/m^3 while the flood peak was falling. The sound of the flowing river gradually disappeared, and the flow velocity gradually slowed until the flow stopped completely. The flow began to stop at 21:48 hrs on the17th, and continued static until 16:18 hrs on the 18th, i.e. the phenomenon lasted 18.5 hours During the period in question, the flow did not stop entirely, it stopped intermittently. The velocity was sometimes higher and sometimes lower. In other words, the flow was intermittent, or "stop - move - stop - move" and so on. This intermittent flow occurred six times from 21:48 hrs on the 17th to 0:10 hrs on the 18th. Each time, when the water head arrived, the stage of cross-section raised 0.1to 0.5 m and that lasted for 2 to 4 minutes.

Chien et al.(1983), also observed the intermittent flow phenomenon in laboratory flume experiments. During the occurrence of a *"mud river"*, the sediment movement is represented by either Model I or Model II. For the case of Model I, when the shear stress acting on the bed is less than the Bingham ultimate shear stress, i.e. $\tau_0 < \tau_B$, and the flowing movement cannot be sustained. According to Qian et al. (1980), when $\rho_m gDJ = \tau_B$ then flow discharges with unit width $q = 0$. For the case of Model II, according to Bagnold (1955), when the volumetric sediment concentration approaches approximately 60%, the flow movement will stop.

SUMMARY AND CONCLUSION

From the discussion above, it is clear that the mechanisms of sediment movement are different between very high and low concentrations. Where hyperconcentration occurs, the decisive condition for the suspension of sediment particles is the Bingham ultimate shear stress (for Model I), or the intergranular dispersive stress (for Model II), but is no longer the vertical turbulent intensity of the flow. The theoretical equations of vertical suspended sediment concentration such as the Rouse equation (Rouse, 1937) i.e.,

$$\frac{C}{C_a} = \left(\frac{D-y}{y} \frac{a}{D-a} \right)^z \tag{6}$$

derived from low sediment concentrations are also no longer applicable for the case of hyperconcentration.

How to describe the vertical distribution of the very high sediment concentration? No theoretical equations have been developed so far because of the complexity of sediment movement for hyperconcentration flow. However, due simply to the very uniform distribution of sediment concentration, it can probably be expressed by a very simple relationship. In the practical works of sediment observations in the Yellow river catchment, the following relation is used.

$$C = C_s \left(1 + \lambda \frac{y}{D} \right) \tag{7}$$

in which, λ is a proportionality factor determined by calibration using the measured data for the different concentrations and C_s is the sediment concentration at the water surface.

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