The Use and Conveyance of Hyperconcentrated Turbid Flows*

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Abstract : A hyperconcentrated turbid flow was diverted to alleviate a shortage of irrigation water in the Baojixia Weihui Irrigation District of Shaanxi Province, China. The original hyperconcentration limit was broken and raised gradually to a maximum sediment concentration of 575 kg/m^3. The turbid flow was transported along canals, originally designed to convey low-concentration water, for up to 200 km without serious deposition of sediment. The benefits of the hyperconcentrated irrigation turbid water : it increases usable water supplies and irrigated acreage, improves soil and crop yield and conserves water and sedimentation in other parts of a river. Properties and measurement of hyperconcentrated flow in an irrigation canal are presented.

Résumé : Un débit chargé hyperconcentré a été dérivé pour atténuer l'insuffisance d'apport d'eau d'irrigation au district d'irrigation de Baojixia Weihei de la province de Shaanxi en Chine. La limite de l'hyperconcentration originelle a été dépassée pour arriver graduellement au niveau de concentration de sédiment maximum de 575 kg/m^3. Le débit chargé a été transporté le long de canaux conçus originellement pour le transport d'eau à faible concentration jusqu'à une distance de 200 km, sans donner lieu à un dépôt de sédiment important. L'avantage de cette eau d'irrigation chargée hyperconcentrée, réside dans le fait qu'elle augmente la fourniture d'eau utilisable et la superficie irriguée, contribue à l'amélioration du sol et du rendement des cultures et à la conservation de l'eau et des sédiments dans d'autres tronçons de la rivière. Les propriétés et la mesure du débit hyperconcentré dans un canal d'irrigation sont présentées.

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* **L'Utilisation et le Transport de Débit Chargé Hyperconcentré**

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Introduction

The Baojixia Weihui Irrigation District (BWID) is located in the lower reaches of the Weihe River, a tributary of the Yellow River. It has an irrigated area of 200,000 ha. Topographically the irrigation district is divided into two parts - an on-plateau system and a down-plateau system. The design capacity of the main canal of the on-plateau system is 50 m^3/s with the flow-direction slope ranging between 0.02% to 0.025%. The down-plateau system has a design capacity of 45 m^3/s with an average slope of 0.033%. The annual rainfall in the district is between 286 mm to 934 mm and the average annual temperature is 14°C. The soils are loam to sandy loam and the slope of the land surface is generally 0.2 to 1.0%.

The Weihe River is a heavily sediment-laden river with a recorded maximum sediment concentration of 831 kg/m^3. In June, July and August there is an average of 15.3 d, with a maximum of 29 d, with concentrations greater than 166 kg/m^3. The range in diameter of suspended particles is 0.0252 mm to 2.8 mm. In BWID the design limit of sediment concentration for diversion is 228 kg/m^3 for the down-plateau system. In order to alleviate a shortage of irrigation water the original hyperconcentration limit was raised gradually on the basis of experience reaching a maximum of 575 kg/m^3. If hyperconcentrated flow is transported to farmland without serious deposition in canals the water may be used for irrigation.

Benefits of Irrigation by Hyperconcentrated Turbid Flow

During 1976-81 nearly 95 M m^3 of flow with a sediment concentration greater than 166 kg/m^3 was diverted to irrigate 50,000 ha of maize and cotton during the growing season to reclaim 6.6 ha of sandy land and used to fill 59 unusable ponds with 75 M t of sediment. During the summer of 1979 about 34 M m^3 of hyperconcentrated water was used which was 15.4% of the water used in the district thus alleviating the shortage. Its benefits are :

1. Water supplies and the irrigated areas are increased and crop yields are improved. Summer crops in BWID suffer seriously from drought. Using hyperconcentrated flow alleviated this problem. It also adds plant nutrients to improve the soil resulting in increased yields of 21% for maize, 22.8% for cotton and 39% for paddy rice over non-irrigated fields. Compared with irrigation using clear water the yield of corn increased by 7% to 11% with the maximum using a concentration of 450 kg/m^3. The yield of cotton was either higher or lower than when clear water was used. The reasons for the increased yield were recognized as :

   (a) the physiological water requirement of the crop was satisfied,

(b) the sediment-laden flood water contained 490 g N (including 45.8 g N hydrolysate and 1500 g P_2O_5 (containing 25.2 g of fixed P_2O_5) per ton of hyperconcentrated water, and

(c) hyperconcentrated irrigation water conserved soil moisture because after each irrigation the deposited silt dried, shrank and pores formed between the silt layer and the soil surface breaking soil capillaries and reducing evaporation.

2. Sandy soils are rehabilitated with sediment of the size of loam particles. Hyperconcentration irrigation can improve sandy soil turning them into highly productive fertile farmlands.

   There are two ways of irrigating : one is to irrigate the barren lands with great amount of turbid water and then plant corn in the fall. The second way is to plant rice on the bank lands on which a thin layer of silt has already been deposited or to irrigate the bank lands with turbid water, which raises the land surface year after year. As the land surface reaches a certain level, two crops (wheat and corn) can be planted in a year.

3. Levelling uneven land. In the irrigation district some lands are cut into trenches and are inconvenient for cultivation and irrigation. By warping with a turbid flow, not only is the water utilized but also the lands are levelled. In 1977 up to 291 large trenches were filled in the district and 1467 ha of croplands irrigated with clear water.

4. Preventing leakage in ponds. In BWID some ponds leak seriously. After hyperconcentrated water was diverted into those ponds the leakage was greatly reduced. In nine ponds with an average impoundment of 55,800 m^3 and an average depth of 2.6 m to 5.5 m of turbid water, the seepage rate was reduced from 300 cm/d to 1.5 cm/d. Warping formed a silt layer on the bottom which reduced the seepage.

5. Conserving soil and water and reducing downstream river sedimentation. Thirty percent of the Yellow River's suspended sediment deposit on its lower reaches which raises the river bed. Between 1976 and 1981 about 75 M t of sediment were used in BWID through hyperconcentration irrigation. Consequently, sediment deposit in the lower reaches of the Yellow River has been reduced by about 22 M t.

Properties of the Hyperconcentration Flow

In the on-plateau system of BWID, hyperconcentrated flows at concentrations of 575 kg/m^3 and 470 kg/m^3 are transported into the field along 200 km without serious sedimentation in the main and lateral canals. Some field canals had deposits due to weak hydraulic intensity. It was noted that due to evaporation and seepage along the canals the sediment concentration at the downstream sections was obviously higher than that of the upstream sections provided no deposition occurred in the canal. For instance, in 1978 the concentration at the headwork of the on-plateau system was 470 kg/m^3 and 170 km from the headwork the concentration rose to 540 kg/m^3. When the sediment load with particles greater than 0.1 mm exceeded 7% of the flow weight a slight deposition occurred at some canal sections and when discharge and velocity of the flow was low slight sedimentation occurred along some sections of the main canal. This case was observed in 1977 when all the river flow of 30 m^3/s with a sediment concentration of over 530 kg/m^3 was diverted into the on-plateau system.

Due to a high concentration of fine particles, the hyperconcentration fluid, with a high viscosity, turned into a non-Newtonian fluid [1]. Therefore the conveyance properties of the hyperconcentration flow are much different from that of ordinary sediment-laden flow.

1. Rheological properties of the Weihe River fluid

Based on experiments conducted with a pressurized capillary viscometer, the Weihe hyperconcentration fluid is approximately that of the Binham Fluid. The relationship between Binham yield stress τ_B and the sediment concentration S is shown in Figure 1. The relationship between τ_B and the fine particle (<0.005 mm) content δ is calculated as $\delta = (1000 — S/2.67)S^{-1}P^{-1}$, in which P is the percent of fine particles in the sediments.

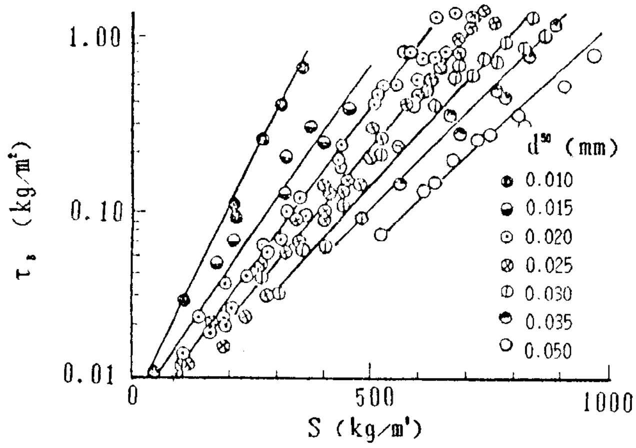

Figure 1. The relationship between Binham yield stress τ_B and the sediment concentration S of the River Weihe hyperconcentrated fluid

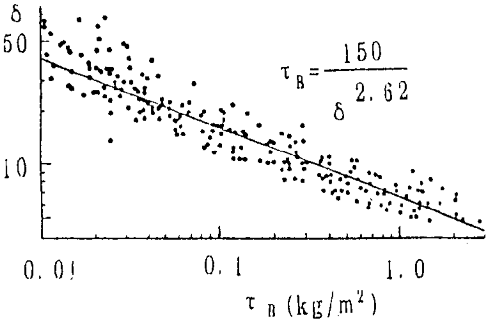

Figure 2. The relationship between τ_B and the fine particle content δ

Based on our tests the rigidity coefficient η of the Weihe fluid is :

$$\eta = \eta_o e^{0.002845} \qquad (1)$$

where η_o is the viscosity coefficient of clear water.

Further laboratory tests showed that the critical non-settling diameter of the sediment particles is :

$$d_o = 4.7\tau_B/(r_s - r_m) \qquad (2)$$

where r_s and r_m are the unit weights of sediment and turbid water respectively.

Field measurements, however, indicated that the real d_o in canals was only one third the laboratory value. This problem should be studied further.

2. The friction resistance of a hyperconcentrated flow

(a) Flows in laboratory tubes and field inverted siphons

Laboratory tests were made in 700 mm x 28 mm inside diameter (id) copper tubes to determine the relation between the drag coefficient (λ) and the Reynolds number (Re) as shown in Figure 3. The flow patterns of both turbid and clear water are divided into laminar, transitional and turbulent regions. The critical Reynolds number (Re_m) is about 2300. In the laminar region $\lambda = 64/Re$ and in the turbulent region λ is greater than in clear water.

In the field the friction of hyperconcentrated water was less than that of clear water in inverted siphons. This is shown by the increased discharge. During hyperconcentration irrigation in 1977 the discharge capacity of the Duanjiawan inverted double siphons each with 2.4 m id and 379 m long (295 m concrete and

84 m steel) rose to 24 m^3/s from the usual capacity of 22 m^3/s. At the Weihui inverted double siphon λ decreased with an increase in concentration of sediment (S). When S > 10% (by weight) λ is a constant (Figure 4).

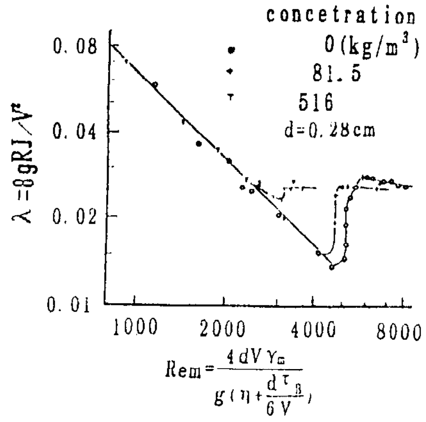

Figure 3. The relation between drag coefficient (λ) and the Reynolds number (Re) in turbid water

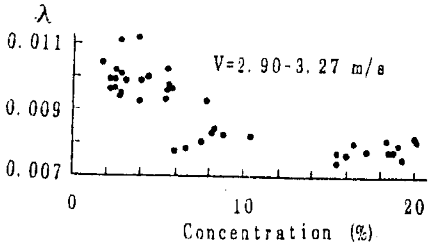

Figure 4. The relation between drag coefficient (λ) and concentration of sediment (S)

(b) Roughness in open canals

Under the condition of hyperconcentration flow in both earth and lined canals without sedimentation, it was observed that the hyperconcentration flow is always in a turbulent state. The roughness of hyperconcentration flow was either higher or closer to that of low-concentration flow (S<5kg/m^3). Measurements in concrete lined canals also indicated that under the same water level the discharge of hyperconcentration flow (S>20 kg/m^3) is 3 to over 10 percent higher than that of low-concentration flow. The main reason for the reduction of roughness under hyperconcentration flow would be the smooth effect of the clay-silt deposited along the boundary of canals. The thickness of the laminar sublayer might be another reason for this.

When canals are, however, under the state of deposition, the roughness of the canals increases due to formation of dunes on the canal bed, no matter what original conditions of the canals are.

3. Critical non-deposit velocity

The critical non-deposit velocity of hyperconcentration flow was evaluated in the term of average cross sectional velocity. It was considered as in the state of non-deposition when thalweg did not deposit and only slight deposit occurred along the side walls, and as in the state of deposition when the thalweg deposited. Based on the field data from BWID and checked with data from Luohui Irrigation District, 50 km from BWID, the non-deposit velocity for lateral and branch canals can be described with the following equation :

$$V^L = 0.15C^{0.45} \tag{3}$$

where V^L = critical non-deposit velocity for lateral and branch canals (m/s); and C = weight percentage of sediment. Equation 3 was valid at the range of C = 10-50% and depth of water where depth $h \ngtr 1.2$ m. Based on the combined data from canals and rivers the critical non-deposit velocity of main canals is :

$$V_M = 0.15C^{0.45} + 0.26\,H - 0.26 \tag{4}$$

where :

V_M = the non-deposit critical velocity for the main canal in m/s,

C = the percentage of sediment by weight, and

H = the depth of the thalweg in metres.

Equation 4 is valid in the range of H = 1.0 m to 3.5 m at C = 30% to 50%.

4. Characteristic of the bed load movement

Under certain conditions the hyperconcentrated flow carries more bed load than the ordinary flow. The increased velocity of bed load in a hyperconcentrated flow is also higher than that in a low concentrated flow. In 1977 up to 124×10^3 m^3/s of bed load was diverted from the headworks of the on-plateau system during hyperconcentration irrigation. The bed load discharge was between 0.32 m^3/s to 0.61 m^3/s while the advance velocity reached 70 m/h. The bed load deposits were cleared during later irrigations with low concentrated flows which carried a bed load of only 1.1% to 2.2% of the capacity of the hyperconcentrated flow. The sediment carrying capacity of a hyperconcentrated flow is attributed to a large unit weight, a high viscosity, a high velocity near the bottom and a large shear stress at the bottom.

Measurements of Hyperconcentrated Irrigations

1. Preparations

Before the flood season one must :

(a) find the sediment carrying capacities of various classes of canals in which the hyperconcentrated flow will be conveyed;

(b) determine the areas to be irrigated, reclaimed and levelled as well as the conditions of the trenches to be filled; and

(c) remove the sediment from the canals, lining the canals where necessary.

2. Forecast and diversion of hyperconcentrated flow

Measurement and forecast of the hyperconcentrated flow in a river has always occurred during the flood season. The hydrographic information at the upstream gauging station is transmitted to the Bureau of BWID by telegram. Meanwhile, sediment measurements are made at the headworks and at every sub-diverting point along the canals. As soon as the flood and sediment information for the upstream gauging station is received the arrival time and sediment concentration are predicted. Plans for the diversion are then determined by water management personnel at the various posts according to their local conditions.

The flow is regulated according to the behaviour of the hyperconcentrated water to avoid deposition in the canals. This is done by :

(a) concentrating hyperconcentrated flows and dispersing the low concentrated flows;

(b) continually carrying a large discharge of hyperconcentrated flow to increase the velocity and reduce deposition;

(c) closing headgates of canals with gentle slopes in advance of the hyperconcentrated flow; and

(d) .determining the hyperconcentrated limit for diversion.

The concentration of sediment of the incoming flow in the Weihe River increases rapidly during the flood period and gradually decreases as the flood recedes. Therefore the concentration of diverted water is low (15%) before the flood and peak sediment load and increases to 25% following the flood peak. The maximum concentration for small floods is set at about 40% and reduced to about 35% for floods with discharges greater than 1000 m^3/s.

3. Comprehensive use of turbid and clear water

When the incoming hyperconcentrated flow in the Weihe River is relatively small and is fully diverted with a high sediment concentration, clear water from the reservoirs within the system is added to the canals to raise the discharge and velocity in order to lower the concentration of sediment. In 1979 at the diversion on the on-plateau system the discharge was only 30 m^3/s and the concentration of sediment was up to 42.4% (575 kg/m^3). At the height of diversion clear water from reservoirs was pumped into the canals. As a result, the sediment concentration was reduced to 30% (370 kg/m^3). The main canals had essentially no sediments deposited. On the other hand the diverting strategies were also emphasized to prevent the bed load from entering the main canals. For example, for a different flood discharge a different diversion ratio of discharge was used to sluice the bed load at the headgate.

After each hyperconcentrated irrigation some lateral and branch canals were silted. It was necessary to clear the deposited sediment. Slight deposits in the main canals and some lateral canals were cleared with a low concentration flow during normal irrigations throughout the year. In this way a silting and erasing equilibrium was maintained.

4. Special water pricing policy

In order to encourage local farmers to use turbid water its price was lowered by 50% or even more during hyperconcentration irrigations.

Application of Irrigation Techniques and Water Measuring Devices

On a field scale of warping, great efforts have been made to extend the small check irrigation method which can control the irrigation norms within the range of 450 m^3/ha to 750 m^3/ha. A level-bottom type of water measuring structure such as the Parshall flume, the rectangular cut-throat flume or the parabolic cut-throat flume [3] were installed in trapezoidal and U-shaped canals to prevent silting from the hyperconcentrated flow.

Summary

The experience gained and lessons learned in irrigating with turbid water from the Weihe River should be useful to other irrigation managers having similar problems.

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