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TENTATIVE PLAN OF PNEUMATIC SILT SCOURING ON YELLOW RIVER

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ABSTRACT

Through analyzing and researching the sand control and sand transportation in Yellow River at present, it comes to the conclusion that the conventional sand holding and sand transportation with water current is an inefficient sand-conveying model. The field measurement data of water and sand regulation of Yellow River in recent years shows that there is no drastic increase of sand. The reason for it is that sand holding and sand transportation themselves absorbs insufficient energy from water current. For the future of Yellow River, this thesis presents a new point of view and train of thought, namely the way of delivering the mud and sand in Yellow River by strengthening the turbulent motion of the water body and drainage of sand with the ascending air current. With the present controlling measures of Yellow River implemented, the future of Yellow River lies in the control of estuary so that the estuary will not become higher and scouring will happen as often as possible. The authors presents in this thesis their own ideas and suggestions.

Key words: pneumatic silt scouring, mud and sand, turbulence, Yellow River

1. INTRODUCTION

The control of Yellow River is a tough task in the world. With the success of the three water and sand regulation tests respectively in 2002, 2003 and 2004, it was declared in 2005 that water and sand diversion would be applied to production and kept as the routine method of controlling Yellow River. Analyzing the sand regulation data of Yellow River, researching the relationship between theoretical and field measurement sand holding and transportation, it can easily come to the conclusion that conventional sand holding and sand transportation are inefficient sand-transporting modes. For the purpose of changing the present condition, the authors propose a pneumatic mode, which may be used for the sand control of Yellow River in the future.

2. THE FEATURES OF THE WATER AND SAND IN YELLOW RIVER

Yellow River is the second longest river in China. The total length of its trunk stream is 5464km; the 3472km long section from the riverhead to Hekou Town is the upper reaches; the 1206km long section from Hekou Town to Taohua Valley is the middle reaches; the 786 km following Taohua Valley is the lower reaches and the section following Lijin is the estuary of Yellow River and is about 178km long. Yellow River is famous across the world for the fact that it is abundant in sand and difficult to control. Its major characteristics are as follows:

The water volume of Yellow Rive accounts for 2% of the total flow volume of the rivers across China. However, from 1919~1960, the annual sand-transporting volume of Shanxian County (Sanmengxia Station) reached 1.6 billion tons in natural conditions with an annual sand concentration of 34kg/m^3, which was much higher than that of the other rivers. The water came from the upper reaches while 90% of the sand came from the middle reaches. Both the incoming water and sand concentrated in the flood season.

The mud and sand in Yellow River mainly deposit at the section between Longmen and Hekou (including the two canyon-style reservoirs at Sanmenxia and Xiaolangdi) and the deposition of mud and sand elevated the riverbed at the lower reaches year by year. At present, the beach face of the riverbed is 4m-6m, in some reach is 10m higher than the ground behind the embankment of Yellow River. Thus, Yellow River has become a well-known perched river.

After completion, Sanmenxia Reservoir blocks the water and sand. Although it has been reconstructed twice and altered in operating method three times, the deposition of sand and mud is still severe in the reservoir area and the reservoir head. The bottom height of the reservoir head at Tongguan is still 5.0m higher than that before the reservoir was built. Thus Weihe River and Luohe River upper than Tongguan have been struck by floods consecutively and this situation urgently needs to be brought under control.

Ever since 1986, the lower reaches of Yellow River have been in low-water season continuously. The sand-transporting capacity of the watercourse has been undermined and the volume of the over-bank flood has been reduced, which has caused the main channel to be seriously silted and weakened the flood-discharging ability，which in turn has caused the phenomenon “small-scale flood, high water level and big overbank”. Coarse mud and sand with a grain diameter longer than 0.05mm account for 76.1% of the deposited substance in the main channel, while those with a grain diameter longer than 0.1 mm account for 50.7% of the substance deposited in the main channel. Research indicates that the mud and sand with a grain diameter shorter than 0.05mm can be drained into the sea together with the water current. Therefore, the major problem of controlling the mud and sand in Yellow River is how to reduce the source of the mud and sand with a grain diameter longer than 0.05 mm and how to drain the mud and sand of such size which have already deposited at the watercourse of the lower reaches into the sea.

3. BRIEF REVIEW OF THE METHODS FOR CONTROLLING THE MUD AND SAND IN YELLOW RIVER

Through the long-term practice of controlling Yellow River, five methods for disposing of and utilizing the mud and sand in Yellow River has been come up, namely, “blocking”, “draining”, “discharging”, “regulating” and “digging”.

“Blocking” means to block and reduce the mud and sand by making full use of the measures for water and soil conservation and the main streams and branches network. According to researches, the 7.86km long region at the middle reaches of Yellow River, which is abundant in sand and coarse sand, is the major source of the mud and sand which cause the lower reaches of Yellow River to be silted. With the measures for water and soil conservation implemented, the grain diameter of mud and sand has become shorter. The water and soil conservation work began in the 1950s and gradually developed after the 1970s. For many years, water and soil conservation measures have reduced the mud and sand entering Yellow River by around 300 million tons on average per annum. Therefore, the effect of reducing sand is remarkable.

"Draining" means to drain the sand into the sea as much as possible by taking advantage of the watercourse at the lower reaches of Yellow River. "Draining" and "regulating" are closely connected with each other. According to researches, in the event that the sand content is 20~30 kg/m^3, the riverbed at the lower reaches will be silted when the flow rate of Yellow River is slower than 2000m^3/s and will be scoured when the flow rate is quicker than 2000m^3/s. Therefore, the let-down rate should be adjusted and controlled to the greatest extent so that it is quicker than 2000m^3/s.

"Discharging" means to discharge the silt to appropriate areas on the two banks of Yellow River, which will not only reduce the mud and sand in Yellow River but also increase arable land, killing two birds with one stone.

"Regulating" means to water and sand regulation. Ever since Xiaolangdi water control project was put into operation in 2001, flood-preventing system has been substantially established at the middle and lower reaches of Yellow River. A united reservoir operating system has been established on the basis of Wanjiazhai Reservoir, Sanmenxia Reservoir, Xiaolangdi Reservoir, Luhun Reservoir, Guxian Reservoir and "man-made flood peak" can be created to drain the sand or drain the sand by density current. Since 2002, the water and sand have been successfully regulated for seven times and the sand at the narrow blocking sections in Tongguan and some places in Shandong Province and He'nan Province has been disturbed by men. After being improved for several times, the tools used for disturbing by man become somewhat more efficient. The watercourse at the lower reaches of Yellow River has been somewhat scoured by regulating the water and sand for several times and the bankfull flow rate has risen to a certain extent. It is reported that the flood-draining capability of the watercourse at the lower reaches of Yellow River has risen from the 1800m^3/s before regulating sand to 3630m^3/s in 2007 (provided by Yellow River web).

"Digging" means to dig out the silt in the river and put the silt thus dug out behind the embankment for reinforcing it. This measure is also frequently taken under appropriate conditions.

4. THE KEY POINTS IN THE COTROL OF MUD AND SAND IN YELLOW RIVER

Yellow River is characterized by the fact there is relatively little water and much sand in it. Although "blocking", "draining", "discharging", "regulating" and "digging" have taken effect, it is still a long-term goal to quickly drain the mud sand newly deposited or deposited earlier in the watercourse into the sea by enhancing the sand-draining capability of water current.

During the course of draining sand, the medium granular sand and fine sand with a grain diameter shorter than 0.05m can be carried into the sea by the flood or when the water and sand are regulated. However, the medium granular sand and coarse sand with a grain diameter longer than 0.05mm will still be left at the lower reaches of Yellow River. Even Sanmenxia Reservoir and Xiaolangdi Reservoir can only drain the fine sand with a grain diameter shorter than 0.05mm or even shorter. It is difficult for the mud and sand deposited in the deep-water area to be drained out of the reservoir. Therefore, it is still cannot be neglected to reduce the mud and sand deposited in the reservoir area and prolong the life of reservoir.

Lowering the height at Tongguan and reducing flood disasters caused by Weihe River and Luohe River are important points of conservancy work.

The control of meandering channel at the lower reaches of Yellow River, the lowering of the river bottom at the river-mouth bar section, the fixation of the flow path and so on.

5. SEDIMENT TRANSPORT CAPABILITY

5.1 Consumption and Absorption of Sand-transporting Energy

Theory proves that traditional way of holding and transporting sand with water current is an inefficient sand-transporting mode.

During the course of water current movement, one part of the energy in the water current is used for overcoming the resistance of the riverbed, one part of the energy is used for suspending the mud and sand in the form of fluctuating energy and another part of the energy is used to carry the bed load. According to the principle of energy consumption, Dou Guoren (1979; 1995) derived the following equation between S_* (water current sand-holding capacity of per unit water body) and q_{sb} (the volume of the transported sand of per unit width of bed load):

$$S_* = \alpha \frac{\gamma\gamma_s}{\gamma_s - \gamma} \frac{n^2 v^2}{H^{4/3}\omega}. \tag{1}$$

$$q_{sb} = \frac{K_o}{C_0^{\,2}} \frac{\gamma_s \gamma}{\gamma_s - \gamma} (v - v_c) \frac{v^3}{g\omega} \tag{2}$$

Wherein γ_ς and γ are respectively the unit weight of mud and sand grains and water; v is the average flowing velocity; v_c is the critical flowing incipient velocity which is expressed in the form of average flowing velocity; H is the depth of water; g is acceleration of gravity; ω is the settling velocity of sediment particles; C_o is scale-free Chezy Coefficient $(C_o = \frac{C}{\sqrt{g}})$; and n is Manning coefficient. After analyzing and reasoning according to the field measurement data and laboratory data of Yangtze River and Yellow River, Dou Guoren found:

$$\begin{aligned} &\alpha = 0.023 \\ &K_o = K_1 K = 0.1 \end{aligned} \tag{3}$$

Wherein K is the coefficient of the water current energy consumed by transporting the bed load along the bottom of the river and bed load in suspended form; K_{1v} is the moving velocity of bed load under the effect of water current. The moving velocity of bed load is lower than that of water current so generally, $K_l < 1.0$. However, there are still short of reliable field measurement data at present. For estimation, let K_l be 0.8 and find that K equals 0.125 according to equation (3). In other words, the energy used for transporting the mud and sand at the bottom of the river only accounts for 12.5 % of the total energy of the water current. Next, according to equation (1), α ,which is the coefficient of the energy consumed by holding sand with water current, equals 0.023. That is to say, 2.3% of the energy in water current is consumed. It is obvious that holding sand with water current is even less efficient than transporting bed silt and suspending sand at the bottom.

5.2 Volume of the Transported Water and Sand by Water and Sand Regulating in Yellow River

As for regulating the water and sand in Yellow River, the regulated sand is at a lower percentage compared with the total volume of the regulated water. Refer to Table 1 for the field measurement volume of the sand and water regulated from 2002 to 2005.

It can be seen from Table 1 that the sand-transporting efficiency at the early stage (2003) is relatively higher after water and sand regulation. The efficiency has reached 4.0~4.2% (t/m^3). Even the highest efficiency in the recent years is only about 1.4%. The average efficiency of the stations in is 1.86%. Compared with the total volume of the water, the percentage of the sand transported is lower than 2%. Therefore, the efficiency is relatively low.

Table 1 Volume of the Transported Water and Sand by Water and Sand Regulating in Yellow River

Year	Hydrological station	Volume of transported water (100 million m^3)	Volume of transported sand (100 million t)	Sand-transporting efficiency % (t/m^3)
2002	Gaochuan	27.1	0.341	1.258
	Lijin	23.2	0.505	2.177
2003	Gaochuan	27.2	1.087	3.996
	Lijin	27.7	1.151	4.155
2004	Gaochuan	22.2	0.180	0.810
(Stage 1)	Lijin	22.3	0.368	1.650
2004	Gaochuan	22.6	0.175	0.785
(Stage 2)	Lijin	22.6	0.326	1.442
2005	Gaochuan	48.2	0.423	0.878
	Lijin	41.8	0.599	1.433
In total	Gaochuan	147.3	2.206	
	Lijin	137.6	2.949	
Average				1.859

However, bound by the conventional concept of transporting sand with water current, people still consider enhancing the sediment transport capacity of water current by increasing the volume of water current so as to prevent the riverbed from being silted. It is suggested that 20 billion tons of water be diverted from Yangtze River and thought that the mud and sand deposited at the lower reaches of Yellow River will be reduced by 360 million tons (This figure substantially conforms to the actual efficiency of water and sand regulation in Table 1). And Xiaolangdi Reservoir will also be used for water and sand regulation. Thus it is believed that the mud and sand deposited at the lower reaches will be substantially eliminated. However, the efficiency of scouring the sand by diverting water from Yangtze River is low. What is washed away is mainly the fine sand with a grain diameter shorter than 0.05 mm which is deposited on the riverbed. It is still not sure whether the coarse sand with a grain diameter longer than 0.05 mm or even longer than 0.1 mm can be washed away.

5.3 Sediment Transport Capacity Measured at Field Indicates Low Efficiency

Li Guoying et al analyzed the field measurement data of the 422 catastrophic floods of Yellow River from 1960 and 1999 and finds that the lower reaches of Yellow River will not be silted if the following equation is satisfied:

$$S=0.0308QP1.5514 \quad (4)$$

Where in S is the sediment concentration at Huayuankou Station; Q is the flow rate at Huayuankou Station（$Q<3000m^3/s$）; P is the percentage of the fine sand in total load with a range from 20% to 92%.

According to the equation (4), S equals 0.0217Q when P equals 80% (fine sand) (d<0.05mm, according to the common definition of fine sand used for Yellow River). That is to say, when Q equals 1000, 2000, 3000 m^3/s respectively, S equals 21.7, 43.4 and 65.1kg/m^3 respectively. The sand-transporting efficiency is not high.

Someone makes use of the analysis of Zhao Ye'an, et al and finds that the sand-transporting efficiency in flood season at Huayuankou Station is as follows:

Qs=1.43Q1.16Supper0.6 (i.e. S=1.43Q0.16 Supper0.6) (5)

When Supper equals 20 kg/m^3 and Q equals 1000, 2000 and 3000 m^3/s respectively, S equals 26.1, 29.1 and 31.1 kg/m^3 respectively. And the efficiency is 2.61%, 2.91%, 3.11%（t/m^3）. Even when S equals 50 kg/m^3, the efficiency is still 4.51%, 5.05%, 5.38 %(t/m^3).

The greatest shortcoming of holding sand with water current is that the turbulent motion of water current is necessary.

The abovementioned theoretical equations of sand holding and sand transporting and the actual efficiency of regulating water and sand in Yellow River have proved that the sand holding and sand transporting with water current in nature are an inefficient method for transporting sand. The causes for it are: ①The sediment capacity depends on the turbulence of water current, which in turns depends on the flowing velocity of the mainstream. The higher is the flowing velocity of the mainstream, the more powerful is the turbulent motion, and the stronger is the sediment capacity. On the contrary, the sediment capacity is weaker if the velocity of the mainstream is lower. ②The velocity of the turbulence depends on the secondary stream of the main stream and is at least two orders of magnitude than the flowing velocity of the main stream. And turbulent motion is out of order and is not in a certain direction. Upward turbulent motion can provide some energy to suspend the mud and sand but the downward turbulent motion will just have negative impact on suspending the mud and sand. ③Turbulent motion depends on the non-uniform distribution of the flowing velocity of the mainstream and will stop instantly once the flowing velocity of the mainstream becomes uniform.

Therefore, the fundamental reason for which natural water current in watercourse has a weak sand-holding ability and can only transport a small amount of sand is the weak turbulent motion. The turbulent motion must be enhanced and the uplifting velocity of the mud and sand must be increased so as to improve the sediment capacity.

6 METHOD OF PNEUMATIC SILT SCOURING

The improvement of the sand-holding ability and sand-transporting ability can't depend on the energy created by the motion of the water current itself. Instead, the turbulent motion of the water current must be enhanced and the flowing velocities must be more non-uniform. By adding one kind of medium into the water, the turbulent motion of water current can be enhanced and the distribution of the flowing velocities can be made non-uniform. At present, it seems that the most efficient and the least expensive medium is air. Thus it comes a new idea or method—"pneumatic silt scouring ".

6.1 Principle of "Pneumatic Silt Scouring"

"Pneumatic silt scouring " is the joint-motion of air, water current and sand which is created by adding air into the bottom of the river.

(1) Velocity of the air current

When the pressure difference is calculated in the form of water column (m), the velocity of air current V (m/s) is

$$V = C_v \sqrt{2g \frac{\rho_w}{\rho_a} \Delta H} \quad (6)$$

Wherein ρ_w、ρ_a are respectively the density of water and that of air; △H is the pressure difference and C_v is air velocity coefficient.

(2) Size of air bubble

If the water is continuously charged with air after air current enters the water, the diameter of the air bubbles running out of the air holes will increase from zero to the longest diameter, $d_{b,\max}$. According to Kobus's study, db max is mainly related to air flow and the acceleration of gravity .

$$d_{b,\max} = (1.295 \sim 1.487)\left(\frac{Q_a^2}{g}\right)^{1/2} \quad (7)$$

Wherein Q_a is the amount of air running out of during per unit time and g is the acceleration of gravity.

(3) Ascending current of air bubbles

According to the study of Haberman and Morton, the velocity of the ascending current of air bubbles is as follows:

$$V_b = 0.716(gd_b)^{1/2} \quad (8)$$

The air bubbles running out of air under the water will expand in volume while ascending with the decrease of pressure. Generally, we can suppose that db max equals 0.03 m when calculating the velocity of the ascending current of air bubbles. Refer to Table 2 for the velocities of the ascending current created by air bubbles with different diameters.

Table 2 Velocity of the ascending current created by air bubbles with different diameters

d_b(mm)	1.0	2.0	5.0	7.0	10.0	12.0	15.0	20.0	30.0
V_0(m/s)	0.071	0.100	0.159	0.188	0.224	0.246	0.275	0.317	0.388

As for the data of the mud and sand in Yellow River, refer to Table 3, which has been made according to Gazette of River Sediment in China of 2002. Listed in Table 3 for comparison are the sinking velocity ω (in the condition of 15℃), the incipient velocity V_c (H=3.0m, H is the depth of water) and the uplifting velocity Us calculated by Sha Yuqing's formula.

Table 3 Characteristic values of the flowing velocity of mud and sand in Yellow River

Name	Longmen	Tongguan	Samenxia	Huayuankou	Lijin	Coarse sand at the middle reaches >0.05mm		
d_{50}(mn)	0.034	0.024	0.028	0.012	0.028	0.05	0.10	0.15
ω(cm/3)	0.0638	0.0318	0.0433	0.0080	0.0433	0.1378	0.5433	1.178
Vc(m/s)	0.582	0.681	0.635	0.950	0.635	0.496	0.399	0.376
Us(m/s)	0.239	0.181	0.205	0.104	0.205	0.325	0.565	0.776

As for the mud and sand in Yellow River, what matters is to transport the coarse sand with a grain diameter longer than 0.05 mm. It can be seen from Table 3 that, compared with the fine sand with a grain diameter of 0.012~0.034 mm, the coarse sand with a diameter longer than 0.05 mm has a little incipient velocity, a high settling velocity and uplifting velocity. That is why the mud and sand of this kind can't be transported over a long distance and the quantity of the transported sand is small.

6.2 Practice of "Pneumatic Silt Scouring "

In China, turbulence was created by laying pipes at the bottom of the tide box for blowing air when Sheyang River model test was conducted in 1970s. The deposition of sediment silted at the downstream of the sluice was scouring. The test of using air-entraining harrow in test hall, the use of aerated silt-entraining harrow under the tidal sluice gate of Xinyang Port in north of Jiangsu Province, the experience of eliminating the silt in the gate slot of the flood-preventing sluice of Changzhou proved that pneumatic silt scouring is efficient. In 2007, a model test of Yan'guan Navigation Lock, which is on Lian (Lianyungang) Shen (Shanghai) Route, was conducted. Because there is 2000m long section in the approach channel was badly silted (The depth of the silt was about 2.0 m and the width of the navigation channel was about 40m) and the silt was difficult to eliminate. Thus "pneumatic silt scouring" was used for the test. The results of the test indicated that the silts (approximately 2m) deposited at the riverbed in dry season can be washed away and the navigation channel won't be silted after pneumatic silt scouring. And the selection of air pressure of air compressor and the arrangement of the pipe apertures in the model are successful (Fig.1；Fig.2).

Figure 1 Air bubbles cloud in clear water

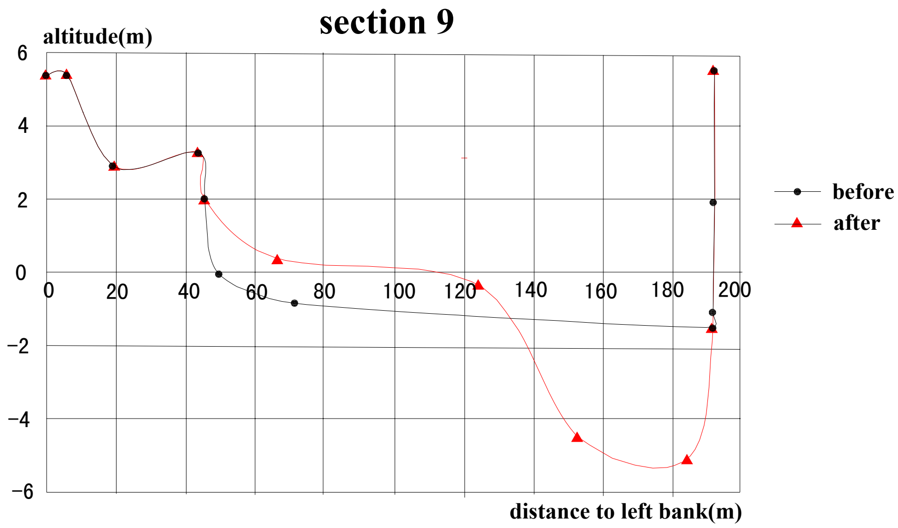

Figure 2 The comparison cross section views before and after the silt is scoured

In Britain, the silt was eliminated at a harbor basin of near Thames River by compressing air. It is said that the expense for it is about 15% of the expense for eliminating the silt by dredging.

6.3 Possibilty of "Pneumatic Silt Scouring" in Yellow River

In principle, the air will run out of the water and creates ascending current which will uplift the mud and sand, only if the air pressure of the air compressor exceeds the pressure created by water depth and deposited sand and the resistance created by pipe and so on. The abovementioned calculation indicates that whether it be fine sand with a grain diameter smaller than 0.05 mm or coarse sand with a grain diameter larger than 0.05 mm or even 0.15mm, the velocity of the ascending current of the air bubbles will far exceed that the settling velocity of the grains of mud and sand. Therefore, the ascending current of the air bubbles is bound to uplift the mud and sand. After being lifted, the mud and sand will be transported over a relatively long distance by relatively weak water current because the settling velocity is relatively lower.

If that pneumatic silt scouring method is applied at the river bottom at Tongguan, the watercourse at the lower reaches, the estuary or the reservoir head of Xiaolangdi Reservoir where the water is relatively shallow, air compressors of low air pressure (0.2Mpa~0.35Mpa, for example) and large capacity can be employed. Air compressors of high air pressure (1.0Mpa~1.70Mpa, for example) can be adopted in front of the dam of Xiaolangdi Reservoir where the water is deep. It can be improved the efficiency of the sand-draining apertures.

7 CONCLUSION

The method of pneumatic silt scouring features the following advantages.

(1) Energy saved, sand uplifted quickly and transported over a long distance;

(2) The pipe apertures will remain unblocked for a long time after the pipes are buried under the riverbed; the sand will be uplifted whenever the air is compressed; and the silt can

be scoured at any time as expected;

(3) The pipes are threatened by the rushing of water but not silt; the mud and sand deposited onthe pipes will be uplifted when air is pumped;

(4) The sediment concertration is high while pneumatic silt scouring method is adopted so the silt can be scoured continuously or large air tank can be employed to store air and scour the silt simultaneously and instantly.

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