Exploration of the Technique 'Detaining the Coarse and Discharging the Fine' for Warping Dam

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Keyword: Warping dam，sediment，sediment retaining benefit，Detaining the Coarse and Discharging the Fine，Loess Plateau

Abstract: An important approach to "Sustaining the Healthy Life of the Yellow River" is to reduce sediment, especially reduce coarse sediment. The warping dams built in the middle reaches of the Yellow River have retained a great quantity of sediment over the years. However, they were all designed on the ideology, "Intercepting and Retaining All Sediment", without allowance for the size-grade distribution of the sediment retained, so trapping a mass of fine sediment. Therefore, when calculating the sediment-retaining benefit of warping dam, only 1/4 of total sediment retention was taken into account, greatly reducing the sediment retaining effect of warping dam on sediment reduction in Yellow River.

Studies have shown that great part of the sediment depositing in the lower reaches of Yellow River is coarse sediment with the grain size of more than 0.05mm. Those fine sediments with the grain size of less than 0.05mm could be discharged to the sea along with water flow. The heavy and coarse sediment areas in the middle reaches of Yellow River is main sediment contribution region. Hydrological observation data shows that the sediment with the grain size of less than 0.05mm accounts for about 50% of total sediment even in coarse sediment concentrated region. Therefore, it is essential to study the measures for effectively dealing with (intercept and detain) coarse sediment coming from coarse sediment concentrated region. This paper explores the technique, "Detaining the coarse and Discharging the fine", for the operation mode of warping dam on the basis of preexisting study results and in combination with the examples of warping dam design, and presents the recommendations to the dam design to increase sediment retention benefit, so that warping dams can play a greater role in "Sustaining the Healthy Life of the Yellow River"

1. Law of Coarse Sediment Movement

1.1 According to the studies, highly concentrated silt discharge will come into being when sediment concentration reaches 200-250kg/m^3 or more. Substantial existence of solid grains in hyperconcentration flow greatly increases the viscosity of turbid suspension. Tests and studies show that for the suspension with the sediment concentration of 300kg/m^3, its viscosity is 2.5-3.5 times of clear water at the same temperature. When sediment concentration reaches 600kg/m^3, its viscosity will be at least 5 times of clear water at the same temperature. This will lead to significant change of the fluid flow in nature. Flow resistance, falling velocity of grains in the fluid flow and sediment carrying capacity will greatly differ with clear water. (Table 3-1) [1].

Table 3-1. Falling Velocity and Average Falling Velocity of Graded Sediment in Hyperconcentration Flow [1]

d_i(mm)	0.35	0.158	0.087	0.061	0.035	0.016	0.008	0.0046	Σ
ω_i(cm/s)	1.676	0.567	0.172	0.084	0.028	0.0058	0.0015	0.0005	
Δp_i	0.015	0.148	0.157	0.205	0.218	0.113	0.02	0.054	1.0
$\Delta p_i \omega_i$	0.025	0.084	0.027	0.0172	0.0061	0.0007	0	0	0.16

1.2 The studies show that highly concentrated silt discharge can change the size-grade distribution of reservoir outflow sediment. Following graph presents the relation between sediment delivery ratio and reservoir/sediment characteristics in a flood of some reservoirs in our country [3]. Where, V is reservoir storage; Q_1 and Q_0 are reservoir inflow and outflow respectively. Horizontal ordinate, VQi/QO2, has the unit of time, meaning the time of a flood staying in reservoir. Besides, sediment delivery ratio of a reservoir is also related to sediment size and concentration. Fine sediment can be discharged out of reservoir more easily than coarse sediment. When sediment concentration exceeds 50kg/m^3, sediment falling velocity will reduce. At the same time, sediment delivery ratio of a reservoir increase [2].

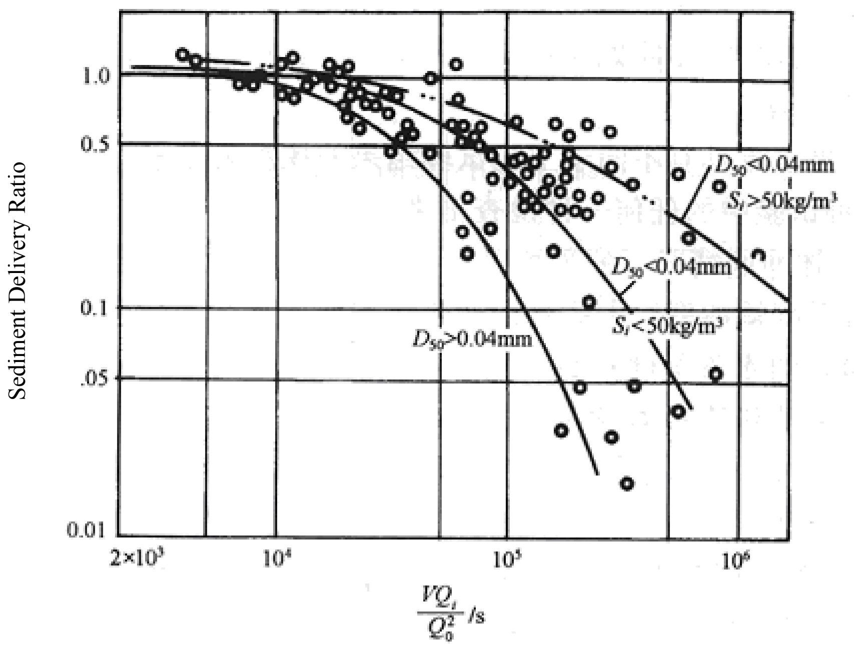

Fig.3-1 Sediment Delivery Ratio - Reservoir/Sediment Characteristics Relation

1.3 The study of hyperconcentration flow characteristics allows us to understand better the state of sediment movement in warping dam.

(1) The floods in small watershed, particularly in heavy and coarse sediment region, are

normally of highly concentrated silt discharge. Before coming into reservoirs, the floods are turbulent flow, entraining a large quantity of sediment. After coming into reservoirs, the floods slow down, and move toward the dams slowly.

(2) Before the floods come into reservoirs completely, reservoir water level ascends gradually. At this time, reservoir outflow normally has the same sediment concentration and gradation as previous state.

(3) After the floods come into reservoirs completely, their flow velocity is nearly zero. Sediments settle down substantially. However, for highly concentrated silt discharge, fine sediments fall much faster than coarse sediments. As per the calculation using Table 1 data, coarse sediments settle down completely several hours after the floods coming into reservoirs, while fine sediments settle-down needs at least 10 hours.

2. Preliminary Demonstration of "Detaining the Coarse and Discharging the Fine" for Warping Dam

With the development of warping dam design technique and the improvement of economic strength, their design and operation can be carried out in a better way to achieve the target, "Detaining the Coarse and Discharging the Fine", so as to build farmland by colmatage and increase sediment-reducing benefit for Yellow River.

2.1 Sediment yield of yellow river main branches

The floods coming from the heavy and coarse sediment areas in the middle reaches of the Yellow River, are largely of highly concentrated silt discharge. Average sediment concentration, obtained by dividing total sediment in flood season by total runoff, normally exceeds 400kg/m^3. Moreover, main tributaries in the middle reaches of Yellow River are not only of highly concentrated silt discharge frequently, but have higher coarse sediment concentration (Table 3-2). Statistical data of individual tributaries in the table shows that 80% of the floods have the sediment concentration of more than 500kg/m^3. Particularly, Huangpu River and Kuye River basins are characterized by extremely coarse loess, where 244 floods have the sediment concentration of more than 1000kg/m^3 [1].

Table 3-2. Sediment Yield of Yellow River Main Branches [1]

Source Region	Tributary	Hydrological Station	Drainage Area（km^2）	Sediment Yielding Modulus（t/km^2.a）	*d*50 (mm)	*P*>0.05 (%)	*S*max (kg/m^3)	Year
Coarse sediment area	Huangpu River	Huangpu	3199	18060	0.079	58	1570	1974
	Gushan River	Gaoshiya	1263	22130	0.046	46	1300	1976
	Kuyehe River	Wenjiachuan	8645	15270	0.069	56	1500	1964
	Tuweihe River	Gaojiachuan	3253	9880	0.069	61	1410	
	Jialuhe River	Shenjiawan	1121	24980	0.045	44	1480	1963
	Wudinghe River	Chuankou	30217	5270	0.040	37	1290	1966
	Dalihe River	Suide	3893	16300			1420	1964
	Beiluohe River	Zhuangtou	25154	3810	0.030	22	1190	1950
	Jinghe River	Zhangjiashan	43216	5920	0.025	20	1040	1963
	Jinghe River	Yangjiaping	14214	6690			900	1979
	Weihe River	Xianyang	16827	4060	0.015	13	729	1968

Fine sediment area	Weihe River	Nanhechuan	23385	6160			953	1959
	Pu River	Maojiahe	7190	6580			992	1965
	Fenhe River	Lancun	7705	1860			544	1973
	Fenhe River	Yitang	23925	597	0.018	17	731	1953
	Jinghe River	Jingchuan	3145	6010			762	1973

2.2 Sediment runoff modulus of both total sediment and coarse sediment should be taken into consideration in the design of warping dam

In order to achieve the target, “Detaining the Coarse and Discharging the Fine”, the design of warping dam should be based on such an ideology that intercept and retain most of coarse sediment; and discharge most of fine sediment.

In the 1.6 billion tons sediments coming to the lower reaches of the Yellow River, there are 0.364 billion tons coarse sediments, accounting for 22.75% of total sediments [1]. Heavy and coarse sediment areas contribute 1.182 billion tons sediments to the Yellow River each year, accounting for 73.88% of total sediment runoff, of which, there are 0.319 billion tons coarse sediments with the grain size of greater than 0.05mm, accounting for 87.64% of total coarse sediment runoff. No doubt, intercepting and retaining this part of sediments, especially coarse sediments, in the numerous gullies and ravines in the middle reaches of Yellow River is of great significance to the control and regulation of Yellow River. Considering the conditional restriction of building dams in the middle reaches of Yellow River and national investment level, the planning and design of warping dam should be based on such a principle in future that retain as much coarse sediment as possible using a limited amount of warping dams.

Therefore, coarse sediment runoff modulus should be taken into account when calculating the sediment retention capacity of warping dam, as follows:

$V = M_0 \times S \times T / D = M \times R \times S \times T / D$

Where, V - Sediment retention capacity, 10^4 m^3;

M_0 - coarse sediment runoff modulus, 10^4 t/km^2;

S - Area of the land under the control of dam, km^2;

T - Sedimentation service life, years;

D - Specific gravity of sediment, t/m^3, generally to take 1.35;

M - Soil erosion modulus, 10^4 t/km^2;

R – Percent of coarse sediment, %.

2.3 Both ordinary flood and design flood should be taken into consideration in the design of water outlet works

The floods in the middle reaches of Yellow River are characterized by “Great runoff and Great sediment” and “Great runoff and Coarse sediment”. Sometimes, the amount of sediment carried by a flood takes up over 60% of yearly sediment runoff. Therefore, attaching importance to the design flood discharge of warping dam is of great value to achieving the target, “Detaining the Coarse and Discharging the Fine”.

On the other hand, ordinary flood carries 40% of yearly incoming sediment. Therefore, “Detaining the Coarse and Discharging the Fine” should also be taken into account for ordinary flood to avoid “Storing the muddy and Releasing the clear” at the time of ordinary flood.

2.4 Increase the flood discharge of outlet works so as to reduce flood detention time and discharge fine sediment out of reservoir.

As per Table 3-1, in hyperconcentration flow, the deposition rate of coarse sediment is above 1m/h (grain size, 0.035mm: 101cm/h; 0.061mm: 302cm/h). Normally, they can settle down completely within several hours. The deposition rate of fine sediment is much less than 1m/h (grain size, 0.016mm: 21cm/h). Complete sedimentation needs longer time. The design of outlet works can be optimized according to this characteristic that there is a greater difference in the rate of deposition between fine and coarse sediments so as to achieve the target, “Detaining the Coarse and Discharging the Fine”.

First of all, increase outlet diameter as appropriate to augment discharge capacity. To achieve the target, “Detaining the Coarse and Discharging the Fine”. It is generally required to discharge overall design flood out of the reservoir within 10 hours. For this purpose, it is needed to increase the discharge capacity of outlet works.

Next, design an outlet works of variable diameter so that the water depth formed by the flood with the same frequency gets lower and lower. For the outlet works with more than one outlets, in order to keep the discharge rate of the outlet works unchanged, outlet diameters should be increased gradually from bottom to top while keeping the outlets at a given interval. To simplify the design, it is advised to furnish an outlet below the crest level of warping dam, and arrange the outlets with larger diameter above the crest level.

For the outlet works with single outlet, it is advised to arrange two or more discharge orifices of different diameters at the same level to suit the floods of different frequency.

2.5 It is essential to operate the outlet works accurately

In order to prevent ordinary flood from open discharge without desilting, and avoid excessive deposition of fine sediment at the time of great flood, it is needed to operate the outlet works accurately, e.g. opening smaller or fewer outlets for small runoff; and opening larger or several outlets for large runoff.

On the other hand, in order to keep as much coarse sediment as possible in warping dam, it is necessary to observe the sedimentation state before warping dam and outlet works after each flood to ensure the lowest outlet above sedimentation level, that is, dead storage, for the convenience of next retention. The exact height of the lowest outlet above sedimentation level shall be figured out by calculating the total volume of coarse sediment under the condition of design flood. Since the interval between outlets is definite, it’s preferred to select upper limit value in actual operation to guarantee that there is sufficient storage capacity to accommodate coarse sediment.

2.6 For changing the control area or sediment retention capacity of warping dam

Based on above ideology, it is advised to increase the control area of key dams and medium dams appropriately, or reduce the sediment retention capacity of warping dam, enhancing the investment benefit and sediment retention benefit of warping dam.

3. Effect of "Detaining the Coarse and Discharging the Fine" for Warping Dam

3.1 Coarse sediment retention benefit of warping dam is increased.

As per preliminary estimate, over 90% of coarse sediment can be arrested, and over 70% of fine sediment can be discharged after the design of warping dam is optimized as mentioned above. In this way, more coarse sediment can be detained in limited reservoir capacity. According to the "Warping Dam Construction Program for Water and Soil Conservation of Loess Plateau Region", 102.8 thousand warping dams will be built in heavy and coarse sediment areas by the year of 2020, providing around 25.0 billion tons sediment retention capacity, which can bring entire heavy and coarse areas under control fundamentally. By applying the method of "Detaining the Coarse and Discharging the Fine", much more coarse sediment can be retained. It is estimated that gross quantity of coarse sediment detained exceeds 12 billion tons.

3.2 Security and stability of warping dam is increased.

After the sediment retention capacity of warping dam is fundamentally filled, its flood retention capacity will begin to be filled, causing rapid decline of its flood control ability. Applying the method of "Detaining the Coarse and Discharging the Fine" can enhance its flood carrying ability considerably. Thus, its defense capability against flood is increased. Relatively, its flood control capability is increased.

3.3 Meaningless consumption of water resources is reduced

Loess Plateau region is characterized by dry climate and great water surface evaporation. Existing design causes the longer residence time of a flood before warping dam, leading to larger reservoir evaporation and severer infiltration. According to our estimate based on the "Warping Dam Construction Program for Water and Soil Conservation of the Loess Plateau Region", annual evaporation due to flood detention by warping dams will reach more than 0.9 billion m^3 in the year of 2020, and more than 0.5 billion m^3 water will be needed to compensate groundwater for infiltration loss due to long-time flood detention (not flow into the Yellow River) in 2020. Totally, river runoff loss will reach 1.5 billion m^3 in 2020, accounting for 18% of total runoff volume, 8.3 billion m^3, available in the control area of warping dams in 2020. "Detaining the Coarse and Discharging the Fine" increases the flood carrying capacity of warping dam to allow the storm flood to pass through in a short time, reducing meaningless water loss due to evaporation and infiltration in the process of long-time residence of flood before warping dam.

4. Design Example

4.1 Beigou Dam, a key dam, is located in the upper reach of Chenjiagou Gully, 40km southeast of Yulin City, Shaanxi Province. The gully is a second-order tributary of Wuding River. The control area of this dam is 6.28km^2. Mean annual erosion modulus is 15,000t/km^2.a. Flood calculation result is given in Table 3-3.

Table 3-3. Flood Calculation Result

Flood recurrence period (year)	10	20	30	50	100	200	300	500

Flood volume (10^4m^3)	16.96	21.25	30.90	35.54	43.33	51.43	57.27	66.44

For flood control standard of the warping dam, 30-year flood was taken as design flood. 300-year flood was taken as check flood. Sedimentation service life, 20 years; Silt retention capacity, $139.56\times10^4m^3$; Flood retention capacity, $57.27\times10^4m^3$; Total storage capacity, $196.83\times10^4m^3$; Dam height, 31.5m, of which, 25.0m for silt retention, 3.2m for flood retention, 2m for free board, and 1.3m for settlement. Outlet works is of inclined pipe. Discharge capacity, $0.82m^2/s$, was designed to pass 20-year flood in three days. Three outlets were provided for simultaneous discharge with 0.45m difference in level and 0.37m diameter.

4.2 As this paper's recommendation, first of all, calculate the quantity of coarse sediment. Coarse sediment runoff modulus is 7000 $t/km^2.a$ in this area, occupying 47% of soil erosion modulus, $1.5\times10^4t/km^2.a$. Annual incoming coarse sediment is $3.26\times10^4m^3$. When the warping dam is operated in the mode, "Detaining the coarse and Discharging the fine", originally designed silt retention capacity, $139.56\times10^4m^3$, will be filled up in 43 years, over one time of originally designed service life.

4.3 In order to achieve the target, "Detaining the Coarse and Discharging the Fine", for both ordinary flood and design flood, it is essential to carry out the design of outlet works.

4.3.1 Outlet works shall be of shaft type. Two discharge orifices of different size shall be furnished at the same level to discharge the floods of different frequency.

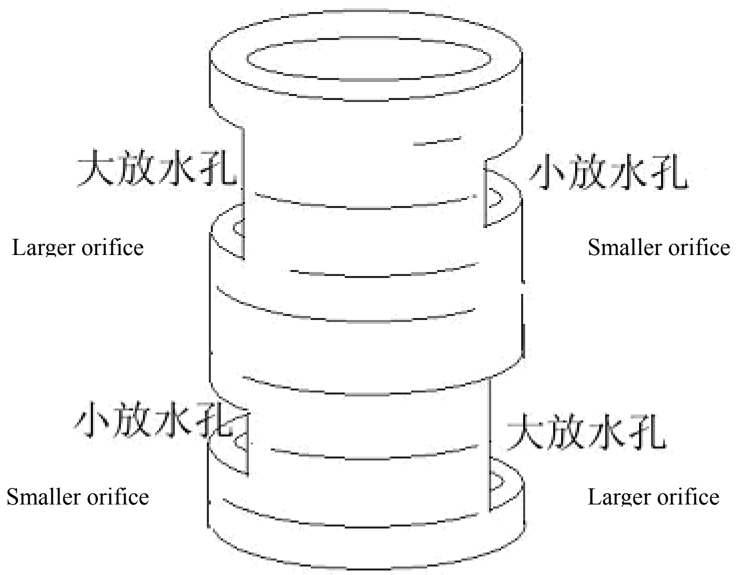

Fig.3-2 Schematic Diagram of Shaft-Type Outlet

4.3.2 Calculate the area of level-1 outlet provided that a design flood ($30.9\times10^4m^3$) shall be discharged in 10 hours; Release rate, $8.6m^3/s$; Difference in level from outlet center to water surface, 1.5m. Outlet area shall be calculated using following formula:

$$d=0.174\frac{8.6}{\sqrt{1.5}}=1.22m^2$$

4.3.3 When the total area of the outlets at each level is 1.22m^2, two orifices of different diameter shall be respectively furnished in the two opposite faces of the shaft at each level to fit the discharge of the floods with different frequency. The two orifices shall respectively have the area of 0.82m^2 and 0.4m^2. The 0.82m^2 orifice will provide 5.77m^3/s release rate and the 0.4m^2 orifice will provide 2.82 m^3/s release rate.

It can be seen from Table 3-4 that the outlets with above diameter combination can basically meet the requirement for discharging a flood in 10 hours. This diameter combination gives attention to both ordinary flood and design flood for "Detaining the Coarse and Discharging the Fine".

Furthermore, the outlets at each level can be provided with more than two orifices of different diameters so as to carry out "Detaining the Coarse and Discharging the Fine" for different floods in a more accurate way.

Table 3-4. Flood Discharge Calculation for Different Recurrence Period

Outlet Diameter (m^2)	Release Rate (m^3/s)	Flood Volume Discharged in 10h (10^4 m^3)	Discharging Flood with Different Recurrence Period		
			Recurrence Period (year)	Flood Volume (10^{4}m^3)	Discharge Duration (hour)
0.82+0.4	8.6	30.96	30	30.90	9.98
0.82	5.77	20.77	20	21.25	10.23
0.82	5.77	20.77	10	16.96	8.16
0.4	2.82	11.88	<10		

4.3.4 Water release culvert and stilling pond shall be designed based on maximum release rate and in accordance with related specification.

4.4 Accurate operation. Since the level-1 outlet is used for water release

It is essential to control the releasing process of each flood. The opening of outlet shall be determined in light of flood volume. The outlet at next level shall be opened promptly when water level has fallen. After each flood, check the sedimentation state before dam, and close the outlets 20cm above and below sedimentation level for next sediment retention.

5. Open Questions

5.1 It is advised to make a further analysis and study of the various branches of Yellow River, especially, sediment gradation and variation of the branches in heavy and coarse sediment areas.

5.2 It is advised to establish a research subject to further study the law of sediment movement in warping dam.

5.3 It is advised to optimize the design of warping dam outlet works so that they can fit the discharge of the floods with different recurrence periods in the operation mode, "Detaining the Coarse and Discharging the Fine".

5.4 It is advised to make a study of how to establish a warping dam operation & management mechanism for "Detaining the Coarse and Discharging the Fine".

References:
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淤地坝“淤粗排细”技术探索

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摘　要：“维持黄河健康生命”的重要内容是减少泥沙，特别是减少粗泥沙。多年来，黄河中游修建的淤地坝拦淤了大量泥沙。但由于是按 “全拦全蓄”设计，没有考虑拦淤泥沙的级配问题，拦淤了大量的细泥沙，因此在计算淤地坝的对黄河的拦沙效益时，仅按总拦沙量的 1/4 考虑，大大降低了淤地坝对于黄河减沙的拦沙效益。

研究表明，淤积在黄河下游河床的泥沙主要是粒径大于 0.05mm 的粗泥沙，粒径小于 0.05mm 的泥沙可以通过水流排入大海。黄河中游的多沙粗沙区是主要泥沙来源区。水文观测数据表明，即使是粗沙集中来源区，其中小于 0.05mm 的泥沙也占 50%左右。因此应当研究粗沙集中来源区高效处理（拦淤）粗泥沙的措施。本文根据已有研究成果，结合淤地坝设计实例，探索淤地坝“淤粗排细”问题，进而提出对淤地坝设计的改进建议，提高拦沙效益，使淤地坝为“维持黄河健康生命”发挥更大作用。

关键词：淤地坝　泥沙　拦沙效益　淤粗排细　黄土高原

1 粗泥沙运行规律

1.1 据研究，当含沙量达到 200-250kg/m^{3}以上时形成高含沙水流，高含沙水流中因固体颗粒大量存在，使浑水悬液粘性明显增高。试验研究表明，对于含沙量为 300kg/m^{3}的悬液，其粘滞系数约为同温度清水粘度的 2.5-3.5 倍，而当含沙量达到 600kg/m^3，悬液粘性达到同温度清水粘性的 5 倍以上。这将导致水流性质的显著变化，使水流的阻力、颗粒在其中的沉速、以及水流挟沙能力等，都与清水显著不同（表 3-1）[1]。

表 3-1　高含沙水流中分级粒径沉速及平均沉速[1]

d_i(mm)	0.35	0.158	0.087	0.061	0.035	0.016	0.008	0.0046	Σ
ω_i(cm/s)	1.676	0.567	0.172	0.084	0.028	0.0058	0.0015	0.0005	
Δp_i	0.015	0.148	0.157	0.205	0.218	0.113	0.02	0.054	1.0
$\Delta p_i \omega_i$	0.025	0.084	0.027	0.0172	0.0061	0.0007	0	0	0.16

1.2 研究表明，由于高含沙洪水特性的影响，使水库排出泥沙的级配发生变化。下图是我国一些水库一次洪峰中的排沙比与水库及泥沙特性之间的关系〔3〕，其中V为库内蓄水量，Qi 及Qo分别为进出库流量，横坐标VQi/QO2 具有时间的量纲，它反映了这一场洪水在水库中停留时间的长短。除此以外，水库排沙比还和泥沙粗细及含沙量有关。细的泥沙比粗的泥沙更容易排出库外；当含沙量超过 50kg/m^{3}时，泥沙的沉速减小，这时水库的排沙比也相应增大〔2〕。

1.3 研究以上高含沙水流的特性，有利于了解淤地坝的泥沙运动状态：

（1）小流域洪水，特别是多沙粗沙区的小流域洪水，基本是高含沙洪水。其在进入淤地坝库区前为紊流，挟带大量泥沙；进入库区后流速降低，洪水缓慢向坝前放水工程流动。

（2）在洪水没有全部进入库前，库区水位逐渐上涨，这时，放水工程排出的洪水含沙量和泥沙的级配基本为入库前的状态。

（3）当洪水全部进入库区后，库内洪水流速接近零，泥沙沉积速度加快，但由于受高

含沙洪水特性的影响，粗沙沉积速度较低，而细沙沉积速度更慢。根据表 1 数据分析，粗泥沙约在洪水入库后的数小时内全部沉积，而细沙则需要 10 小时以上的沉积时间。

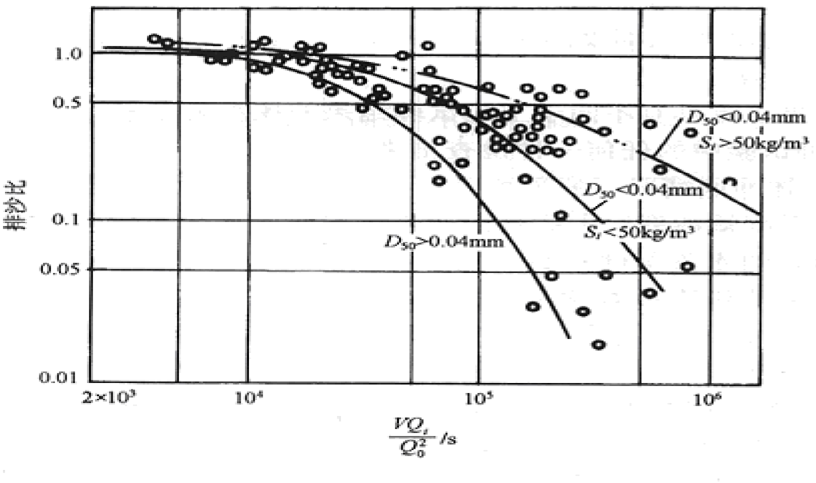

图 3-1 水库排沙比与水库及泥沙特性之间的关系

2 淤地坝“淤粗排细”的初步论证

随着淤地坝设计技术的发展和经济实力的提高，可以更加深入、细致的对淤地坝进行设计和调控，实现“淤粗排细”，使其不仅能够淤地造田，而且提高为黄河减沙的效益。

2.1 黄河主要支流产沙概况

来自黄河中游黄土丘陵沟壑区的洪水多为高含沙洪水。用洪水期总沙量除以总水量所求得的平均含沙量一般均超过 400kg/m³。其中，黄河中游的主要入黄支流不仅经常发生高含沙洪水，而且其中的粗沙含量较高（表 3-2）。据对表中所示各支流的统计表明，80%的洪水的含沙量均超过 500kg/m³。黄甫川和窟野河流域的黄土组成极粗，244 次洪水的含沙量均超过 1000kg/m³〔1〕。

表 3-2 黄河主要支流流域产沙〔1〕

来源区	支流名	站名	流域面积（km²）	产沙模数（t/km².a）	d50 (mm)	P>0.05 (%)	Smax (kg/m³)	发生年份
粗泥沙来源区	黄甫川	黄甫	3199	18060	0.079	58	1570	1974
	孤山川	高石崖	1263	22130	0.046	46	1300	1976
	窟野河	温家川	8645	15270	0.069	56	1500	1964
	秃尾河	高家川	3253	9880	0.069	61	1410	
	佳芦河	申家湾	1121	24980	0.045	44	1480	1963
	无定河	川口	30217	5270	0.040	37	1290	1966
	大理河	绥德	3893	16300			1420	1964
细泥沙来源区	北洛河	状头	25154	3810	0.030	22	1190	1950
	泾河	张家山	43216	5920	0.025	20	1040	1963
	泾河	杨家坪	14214	6690			900	1979
	渭河	咸阳	16827	4060	0.015	13	729	1968
	渭河	南河川	23385	6160			953	1959
	蒲河	毛家河	7190	6580			992	1965

汾河	兰村	7705	1860			544	1973
汾河	义棠	23925	597	0.018	17	731	1953
泾河	泾川	3145	6010			762	1973

2.2 淤地坝设计中应同时考虑全沙输沙模数和粗沙输沙模数

为了实现“淤粗排细”，淤地坝的设计思路应是：拦淤大部分粗沙，排出大部分细沙。

进入黄河下游的16亿t泥沙中，粗沙有3.64亿t，占总沙量的22.75%〔1〕。其中多沙粗沙区每年输入黄河的泥沙达11.82亿t，占同期黄河输沙总量的73.88%，其中粒径大于0.05mm的粗泥沙3.19亿t，占粗泥沙输沙总量的87.64%。在黄河中游的千沟万壑中拦淤这些泥沙，特别是粗泥沙，无疑对黄河治理具有重要意义。考虑到黄河中游地区建坝条件的限制和国家资金投入水平，以有限的淤地坝拦淤尽可能多的粗沙，应当是今后淤地坝规划设计的基本原则。

据此，在计算淤地坝拦沙库容时应当考虑粗沙输沙模数，并以此为依据，计算拦沙库容。

建议，拦沙库容计算公式为：

$V=M_0\times S\times T/D=M\times R\times S\times T/D$

式中 V—拦泥库容，万m^3

M_0—粗泥沙输沙模数,万t/km^2

S—坝控面积,km^2

T—淤积年限,年

D—泥沙比重，t/m^3,一般取1.35

M—土壤侵蚀摸数,万t/km^2

R—粗泥沙比例，%

2.3 放水工程设计应同时考虑常遇洪水和设计洪水

由于黄河中游的洪水特点是“大水大沙”，而且“大水粗沙”。往往一场大洪水所携带的泥沙就占全年总沙量的60%以上。因此重视对淤地坝设计洪水的排泄，对于实现“淤粗排细”具有重要意义。

同时，由于常遇洪水携带约40%的年来沙量，因此也要考虑对常遇洪水的“淤粗排细”，避免造成常遇洪水的“拦浑排清”。

2.4 加大放水工程的泄洪量，减少洪水的拦滞时间，将细泥沙排出

由表3-1数据知，在高含沙洪水中，粗沙沉积速度每小时1m以上（粒径0.035mm：101cm/h，粒径0.061mm：302cm/h），一般可以在数小时内完全沉积；而细沙沉积速度每小时远小于1m（粒径0.016mm：21cm/小时），全部沉积需要更长的时间。根据粗沙和细沙沉积速度有较大差异的特点，可以通过改进放水工程的设计，达到“淤粗排细”需要。

首先，适当加大放水工程放水孔直径，增大泄流量。为了实现“淤粗排细”，一般应当在10小时内排泄完一场设计洪水总量。为此需要加大放水工程的泄洪流量。

其次，设计变孔径的放水工程。随着库容的淤积，相同频率的洪水形成的水深越来越浅。对于多孔排水的放水工程，为了保证放水工程的泄流量不变，在放水孔间距一定的条件下，放水孔径应由下向上逐渐增大。为简便设计，可以在拦泥坝高高程以下为一个孔径尺寸，拦泥坝高高程以上为加大的孔径尺寸。

对于采用一孔排水的放水工程，可以在同一高程设计两个（或两个以上）不同孔径的排

水孔，以适应排放不同频率的洪水。

2.5 精确调控放水工程

为了防止常遇洪水不经沉沙而畅泄和大洪水细沙沉积过多，需要对放水工程进行精细调控：小水开小孔，少开孔；大水开大孔，多开孔。

其次，为了保证将粗沙尽可能多的拦在淤地坝内，应当在每次洪水过后对淤地坝和放水工程处的淤积情况进行观测，使最低的放水孔高于淤积面，相当形成一定的死库容，以利下次拦淤。最低放水孔距离淤积面以上的确切高度应通过计算在设计洪水条件下粗泥沙的总体积获得。由于在运行期的淤地坝放水孔间的距离是确定的，因此实际操作中最好取上限值，以保证有足够的库容拦淤粗沙。

2.6 改变淤地坝的控制面积或拦沙库容

根据以上思路，可以考虑适当加大骨干坝和中型淤地坝的坝控面积，或减小淤地坝的拦泥库容，提高淤地坝工程的投资效益和拦沙效益。

3 淤地坝实行“淤粗排细”的效应

3.1 提高了淤地坝拦淤粗泥沙效益

初步估算，采用以上改进设计，淤地坝可以拦淤90%以上的粗沙，同时排出70%以上的细沙，从而使有限的库容拦淤更多的粗沙。以《黄土高原地区水土保持淤地坝规划》的建设规模，到2020年在多沙粗沙区建设10.28万座淤地坝，形成约250亿t的拦沙库容，基本控制全部多沙粗沙区。如果采用“淤粗排细”方式建设这些淤地坝，可以显著增加粗沙拦淤量，估算总粗沙拦淤量超过120亿t。

3.2 提高了淤地坝安全稳定性

淤地坝在淤积库容基本淤满后，开始淤积防洪库容，造成淤地坝的防洪能力急剧下降。实行“淤粗排细”后，显著加大了淤地坝的泄洪能力，从而使淤地坝提高了防御洪水的能力，相对提高了淤地坝的防洪能力。

3.3 减少了水资源的无效消耗

黄土高原地区气候干旱，水面蒸发量大。现行的设计，造成洪水在淤地坝内滞留时间较长，库区蒸发和下渗量较大。根据《黄土高原水土保持淤地坝规划》框算的结果，到2020年，每年淤地坝由于滞洪造成的蒸发达9亿多m^3；由于长时间滞洪造成的下渗补充地下水（不进入黄河的水量）在2020年达5亿多m^3，两项合计，2020年损失河川径流达15亿m^3，占2020年坝控面积内83亿m^3径流总量的18%。“淤粗排细”加大了淤地坝的排洪能力，使暴雨洪水在短时间内排出，减少了淤地坝在长时间滞洪情况下的水量蒸发、下渗等无效损耗。

4 设计举例

4.1 北沟骨干坝位于陕西榆林城区东南40km处的陈家沟上游，坝址所在沟道属无定河二级支流。坝控面积6.28km^2。多年平均侵蚀模数为1.5万t/km^2.a。洪水计算成果见表3-3

表3-3 洪水计算成果表

洪水重现期（年）	10	20	30	50	100	200	300	500
洪水总量（万m^3）	16.96	21.25	30.90	35.54	43.33	51.43	57.27	66.44

防洪标准按 30 年一遇洪水设计，300 年一遇洪水校核，淤积年限取 20 年。拦泥库容 139.56 万m^3，滞洪库容 57.27 万m^3，总库容 196.83 万m^3。坝高 31.5m，其中拦泥坝高 25.0m，滞洪坝高 3.2m，安全超高 2m，沉陷加高 1.3m。放水工程为卧管，设计泄流量按 3 天泄完 20 年一遇一次洪水总量计算，泄流量为 0.82m^3/s，采用同时开启 3 孔泄流，孔间水位差 0.45m，计算孔径 0.37m。

4.2　根据本文建议，首先要计算粗沙数量。该区域粗泥沙输沙模数为 7000t/km^2.a，占土壤侵蚀模数 1.5 万t/km^2.a的 47%。年来粗沙 3.26 万m^3。当采用淤粗排细方式运行时，原设计的 139.56 万m^3拦泥库容的淤积年限可达 43 年，比原设计淤积年限增加一倍以上。

4.3　为了达到对常遇洪水和设计洪水均实现“淤粗排细”，要进行放水工程设计。

4.3.1　选择竖井形式的放水工程，采用相同高程设计两个不同面积的放水孔，以排泄不同频率的洪水。

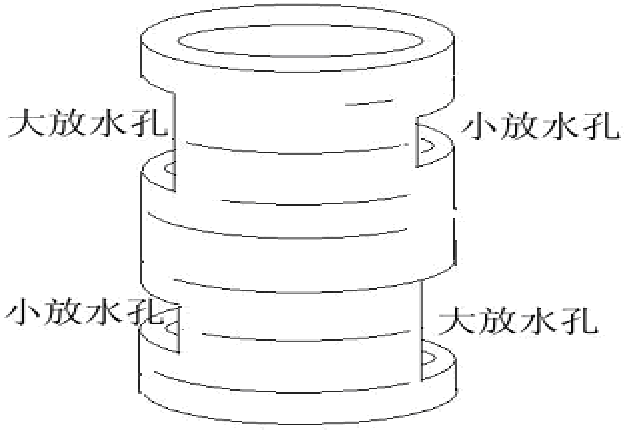

图 3-2 竖井放水孔设计示意图

4.3.2　按 10 小时左右泄完一次设计洪水（30.9 万m^3），计算 1 级孔放水时的竖井放水孔面积。放水流量为 8.6m^3/s。孔口中心至水面深 1. 5m，计算孔面积

$$d=0.174\frac{8.6}{\sqrt{1.5}}=1.22m^2$$

4.3.3　每级放水孔总面积 1.22m^2时，在竖井每级的相对两面分别设计不同孔径的放水孔，以适应不同频率洪水的排泄。设相对两孔面积分别为 0.82m^2和 0.4m^2。其中 0.82m^2的放水流量为 5.77m^3/s，0.4m^2的放水流量为 2.82m^3/s。

表 3-4　排泄不同重现期洪水试算表

孔径组合（m^2）	放水流量（m^3/s）	10 小时排完的洪水总量（万m^3）	重现期（年）	排泄不同重现期洪水	
				洪水总量（万m^3）	排泄时间（小时）
0.82+0.4	8.6	30.96	30	30.90	9.98
0.82	5.77	20.77	20	21.25	10.23
0.82	5.77	20.77	10	16.96	8.16
0.4	2.82	11.88	<10		

从表 3-4 看出，采用以上组合孔径能够基本满足十小时左右排泄完一次洪水总量的要求。该组合孔径兼顾了设计洪水和常遇洪水的“淤粗排细”要求。

进一步考虑，还可以将每级放水孔设计成 2 个以上的组合孔径，以更精细的对各类洪水进行“淤粗排细”方式的排泄。

4.3.4　对于放水涵洞、消力池等按照最大放水流量和规范要求设计。

4.4　精细调度

由于采用一级放水孔放水，因此需要对每场洪水的放水过程进行控制，按照洪水总量决定需要开启多大的放水孔，并在水位下降后，及时开启下一级放水孔。每场洪水过后，应检查坝前淤积情况，及时关闭位于淤积面上下 20cm 左右的放水孔，以利下次拦沙。

5　需要进一步研究的问题

5.1　深入分析研究黄河各支流，特别是多沙粗沙区支流的泥沙级配及其变化。

5.2　设立研究课题，进一步研究淤地坝中泥沙的运行规律。

5.3　对淤地坝放水工程的设计进行改进，使之适应“淤粗排细”条件下，排泄不同重现期洪水的要求。

5.4　研究如何建立在“淤粗排细”要求下的淤地坝运行管理机制。

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