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PROGRESS OF SEDIMENTATION RESEARCH FOR THE YANGTZE RIVER

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Abstract: This paper presents an overview on the progress of sedimentation researches for the Yangtze River over the past 50 years, including water/sediment movement, channel evolution, river training and solutions to sedimentation problems of large hydraulic projects built on the Yangtze. A number of significant problems to be further studied are proposed herein.

Keywords: Yangtze River, Sediment movement, River training, Hydraulic project

1 INTRODUCTION

Taking its source from the snowcapped Mt. Geladandong on the Qinghai-Tibet Plateau, the Yangtze maintream stretches more than 6,300 km and drains an total area of 1.8 million km^2, with a gross hydraulic fall of 5,400 m. It is the largest river in China and the third largest in the world. As illustrated in Fig. 1, the river upstream of the city of Yichang is referred to as the Upper Reach, which is 4,500 km in length and has a drainage area of 1 million km^2, where the river on its Upper Reach flows in rapids through high canyons with large surface gradients except in the headwaters area. The well-known Three Gorges between Fengjie and Yichang is the final 200km stretch of upper Yangtze. The Middle Reach extends from Yichang downstream to Hukou, 955 km long and having a drainage of 0.68 million km^2, where the river runs in small surface gradient through flat floodplains with many lakes, and dike systems are built on both banks. Further downstream of Hukou is the Lower Reach, which is 938 km long and has a drainage area of 0.12 million km^2. There is a 600 km section of the Lower Reach downstream of Datong affected by tidewater.

The Yangtze is a huge water system comprising a multitude of tributaries and lakes, large and small. There are 437 tributaries whose drainage areas each are larger than 1000 km^2; 49 tributaries larger than 10,000 km^2; and 4 tributaries-namely Yalong River, Minjiang River, Jialing River and Hanjiang River-larger than 100,000 km^2. Among all the tributaries, the Jialing River, 160,000 km^2 of drainage area, is the largest. A total area of 15,200 km^2 is occupied with lakes in the middle and lower Yangtze Basin, with Lake Donting and Lake Poyang as the largest ones. The Lake Dongting first receives inflow from four rivers-Xiangjiang River, Zishui River, Yuanjiang River and Lishui River, and four inlet channels-namely Songzikou, Taipingkou, Ouchikou and Tiaoxiankou(gated since 1959), sharing some inflow from the Yangtze mainstream. It drains finally into the Yangtze at Chenglingji. The Lake Poyang takes in water from five rivers-Ganjiang River, Fuhe River, Raohe River, Xiushui River and Xinjiang River, and then drains into the Yangtze at Hukou.

The Yangtze maintains ample amount of water with relatively small sediment concentration, but the amount of sediment load is huge. Observation at the Yichang Hydro-station gives a long-term mean annual runoff of 438.1 billion m^3 and sediment load of 0.501 billion tons; while the observation of the same kind at the downstream Datong Hydro-station shows 905.1 billion m^3 of annual runoff and 0.433 billion tons of sediment load.

Fig.1 A Sketch Map of Yangtze River Basin

The Yangtze River has rich hydraulic power potential and is also deemed as a gold waterway for transportation, but its floods are recurring and severe. Ever since 1950s, the Changjiang Water Resources Commission (CWRC) has carried out extensive monitoring and studies on hydrology, sedimentation and fluvial evolution with plenty of findings accumulated, which have served as scientific basis for regulation and development of the Yangtze. In the same period, a master plan for comprehensive utilization of water resources in the Yangtze Basin has been formulated. A number of projects as envisioned in the master plan have either been implemented or underway, such as Danjiangkou Project, Gezhouba Project, Three Gorges Project, East and Middle Routes of S-N Water Transfers, and river channel training on the middle and lower reaches.

2 RESEARCH ON WATER/SEDIMENT MOVEMENT AND FLUVIAL EVOLUTION

Systematic monitoring of hydrology, sediment load and fluvial change have been conducted on the mainstream as well as on major tributaries and lakes by CWRC since 1950s, by means of setting-up a complete monitoring network comprising hydro-stations and river channel instrumentation agencies. The adequate data accumulated in this way have not only helped appreciation of the behavior of sediment load movement and evolution process of rivers and lakes, but also laid a sound foundation for rehabilitation and development of the Yangtze River Basin.

2.1 Researches on Water Flow Model

Since 1959, the water flowing characteristics at bends of the Yangtze have been systematically analyzed, including flow surface states, dynamic flow axis changes, and transverse circulation structure, resulting in working out of the calculation formula, for the localities at river bend, of vertically-averaged flowing velocity, curvature radius of dynamic flow axis, and the mathematical expression for location of the direct impact by the major flow.

Observed data have been analyzed to investigate the flow structure, movement behavior, velocity distribution and flow resistance at both flow split and convergence areas of river forks.

In view of the disparity between the reaches of broad valley and narrow gorge, observed data analysis and in-lab flume test have been done to study the flow turbulence, resistance and velocity distribution for both cases. Starting from Reynold's equation, a time-average velocity distribution equation is derived, which can reflect the effect of sidewalls.

2.2 Research on Sediment Movement

A lot of systematic research findings have been derived regarding the rule of sediment movement in the Yangtze River in the past half century, in response to the needs arising from regulation and development of the Yangtze.

(1) Sediment characteristics

On the basis of field investigation and sampling, the grain components and mineral composition of the suspension sediment load on upper reaches and the riverbed sediment on middle and lower reaches have been analyzed. In addition, geomorphologic and mineralogical approaches have been applied to investigate the bedload of cobbles on the reaches of the Yangtze reaches flowing within Sichan Province (known as Chuanjiang Section), figuring out the cobble inflow from major tributaries on 'Chuanjiang Section' and the cobble outflow at Nanjiguan, the downstream outlet of Three Gorges. In the process, a model is developed to estimate cobble discharge by application of sediment mineralogical approach.

(2) Sediment incipient motion rule

Since 1950s, as required by the design of Gezhouba and Three Gorges Projects as well as river training, a variety of instrumentation and tests have been performed, which include sediment load measurement at hydro-stations, field test with marked cobbles in motion, field and in-lab flume tests on cobble incipient motion, in conjunction with theoretical analysis. As a result, knowledge is gained in relation to bedload incipient motion mechanism and relevant factors, with the equation of sediment incipient velocity formulated, which is further detailed by means of statistical theory to apply specifically to uniform and non-uniform grain sediments. In late 1980s, based on prototype monitoring data and theoretical exploration, more incipient velocity equations respectively for clayey fine particle sediment, loose particle sediment and cobble were proposed.

To meet the needs for design of Lower Jingjiang Stretch river bend cutoff, scour-resistance tests for clay were conducted in 1960 and 1965, using the undisturbed soil specimens sampled from the two sites of river cutoff projects respectively. The data obtained were re-analyzed in 1987 with theoretical tools, deriving the calculation formula of scour-resistance capacity of clay versus flow velocity.

(1) Sediment carrying capacity of flow

The sediment carrying capacity calculation formula applicable to middle and lower reaches of the Yangtze and lakes in the area have been proposed on the basis of investigating the extensive data collected from middle and lower Yangtze mainstream, Sanmenxia Reservoir, Guanting Reservoir, and Danjiangkou Reservoir, together with in-lab flume experiments.

(2) Sediment transport

In order to study the scour and deposition of sediment in the fluctuating backwater zones of both Gezhouba and Three Gorges reservoirs, field investigations and both field investigation and in-lab flume tests were undertaken during 1950s to 1980s to study, particularly for 'Chuangjiang Section', the morphological features, motion and on-the-riverbed accumulation characteristics of cobbles. Many insights into the bedload movement were obtained, and the empirical bedload transport curve was put forth.

2.3 Researches on Fluvial Evolution

In the past 50 years, on the basis of channel shifting monitoring, sediment movement mechanics in combination with geomorphology has been applied to study the historical changes and recent evolution of the Yangtze River channel, relationship between rivers and lakes, genesis of meandering and braided channels, etc. The accumulated research findings have provided a sound basis for channel regulation and development.

2.3.1 River Development in Yangtze Headwater Area

In 1976, CWRC in collaboration with relevant agencies conducted, for the first time in history, a field investigation to the headwater area. At that time, the Tuotuo River is justified as the primary source of the Yangtze, with which as the basis to re-estimate the length of the Yangtze being 6,300 km, ranking the third in the world. A revisit to the headwater area took place in 1978, when further fresh appreciation of the area were attained: the river system in the headwater area is under strict control of geotectonic structure; the headwater river system eventually came into being in mid-Pleistocene; the development of river valley is closely related to differential tectonic lift of the Plateau and the last three times of glacial actions since mid-Pleistocene; the headwater rivers can be morphologically divided into 2 different types, i.e. trapezoid- or U-shaped cross-section mountainous rivers and broad/shallow braided meandering rivers on high-altitude plain; Tuotuo River, Dangqu River and Chuma'er River are ascertained to be the Primary Source, Southern Source and Northern Source of the Yangtze, respectively.

2.3.2 Source of Sediment

Since 1970, as required by Three Gorges Project and Gezhouba Project, sediment contribution data have been collated and analyzed, giving the results that sediment supplies from Jinsha River and Jialing River are respectively 46.7% and 30.9% of the sediment load passing Yichang, therefore the two rivers are the major contributor of sediment on the upper Yangtze reaches. In terms of sediment transport modulus, the sediment contributing areas on the upper reaches are classified according to various degree of erosion into four groups: slight, medium, strong and intensive. A contour map is plotted with erosion modulus data for the upper Yangtze reaches.

2.3.3 Channel Shifting on Middle and Lower Reaches

(1) Meandering channel shifting

Since 1950s, as needed by Jingjiang Stretch regulation, Yangtze River Scientific Research Institute has undertaken systematic studies on water/sediment movement, river morphology, bank and riverbed structure, channel shifting mechanism and the interrelationship between Jingjiang Stretch and Lake Dongting. A study report on the characteristic of Jingjiang Stretch was developed in 1974.

In order to address the shifting and regulation Lower Jingjiang Stretch, monitoring data of 12 meandering rivers in South China have been collected, and with these as the basis in-lab riverbed model was established to study the genesis of meandering channels. As a result, the basic conditions and elements contributing to evolution of meandering channels are brought to daylight.

(2) Braided channel evolution

Based on the monitoring data of Yangtze mainstream and tributary channels in middle and lower basin, systematic studies have been done to address such issues of braided channels as historical shifting process, riverbed boundary conditions, water/sediment movement, river morphology and its relationship with factors of hydraulic, sediment and fluvial characteristics, river arm and sediment bar evolution modes, and regulation approach for braided channels. The conditions of braided channel generation and regulation principles are ascertained and formulated on both mainstream and tributaries in middle and lower Yangtze Basin.

3 RESEARCH ON RIVER TRAINING OF THE MIDDLE AND LOWER YANGTZE

3.1 River Training Planning

River training planning is the guideline under which to implement the channel regulation works. It has ever been the focus of CWRC in its efforts to regulate the middle and lower

Yangtze channels. A preliminary planning of this kind was carried out during 1950s to early 1960s, with formulation of the *Outline Planning Report on Middle and Lower Yangtze Mainstream Channel Regulation.* From mid-1960s regime control planning was started, and in 1965 a river regime control planning report for Datong-Zhenyang reach was developed, in which the target, tasks, approach, measures and outline scheme of regime control were defined. For consolidating the effect of Lower Jingjiang Stretch cutoffs, improving flood control and navigation conditions and further stabilizing the regime on the Stretch, regime control planning was deployed in 1970s, leading to the implementation of regime control works on the Lower Jingjiang Stretch in 1984 with approval from the then Ministry of Water Resources and Electricity. In early 1990s, as the tasks of channel regulation and shoreline development became more and more imperative and urgent, CWRC commenced in 1992 the regulation planning of middle and lower Yangtze mainstream channel, with a planning report in this regard developed in 1997. To foster sustainable socio-economic development in the estuary area, comprehensive regulation and development planning was initiated in 2002 for the estuary with the planning report finalized in June 2004.

3.2 Channel Regulation

In the last 50 years, a lot of revetment, cutoff, fork blocking and regime control works have been implemented, playing an important role in controlling flood, protecting bank lines and stabilizing river regime.

3.2.1 Bank Protection Works

Out of the 1,900 km long middle and lower reaches, 1,500 km (42% of the total length) long bank lines have suffered collapses. The most intensive bank collapses occur on some reaches with tens or even hundreds of meters width of collapsing bank per year. Collapse of bank lines not only changes the channel morphology and river regime, but also imposes great damages on flood control and economic development for communities on both banks.

Bank protection works have been constructed in the last half-century in order to impede such undesirable situation. The Yangtze bank protection works has a long history. As early as in 1465, local bank protection works was built on the Jingjiang Stretch dikes. However, massive construction of such works started from 1950s. As of 1997, 1,200 km (80% of the total collapse-suffering length) bank lines have been placed with revetments, including 70 million m^3 of riprap, 3.3 million sunk tree fagots, 4 million m^3 dumped pillow structure, 685 groins and 20 km long training levees. In the wake of 1998 extra large floods, many more bank protection works have been built, including, as of by the end of 2002, 24.6 million m^3 of dumped riprap and 1.1 million m^2 of sunk mattress of various types. All these works have contributed significantly to flood control, regime control, shoreline stabilization as well as national economy development.

In parallel to bank protection works construction, a large number of in-situ monitoring and lab tests have been done for such works, including displacement of bank protecting rocks under channel scour action, falling range of dumped rock and its probabilistic distribution, flow structure and local scouring features on different types of bank protection works; failure mechanism and applicability of jointed concrete mat, moulded concrete bag, sand pillow bag, pervious tetrahedron frame, and flexible mat. Shallow-depth stratum profiler and self-made underwater sonar were employed to detect the distribution of rock blocks on riverbed as revetment. All the findings derived in above process have been quite applicable to guiding practice. Technical specifications associated with bank protection works design was formulated in 1993 and later updated in 2000.

3.2.2 Cutoff Works

The river bend cutoff works of the Lower Jingjiang Stretch is an important component for flood control. Various alternatives were studied and justified in 1960 with reference to similar previous practices on 18 rivers both domestic and abroad. The final scheme was selected, involving 3 sections to be straightened, namely Shatanzi, Zhongzhouzi and Shangchewan (see Fig. 2)

Zhongzhouzi Cutoff and Shangchewan Cutoff were constructed in 1967 and 1969, respectively. In addition, a natural cutoff occurred on Shatanzi river bend in 1972.

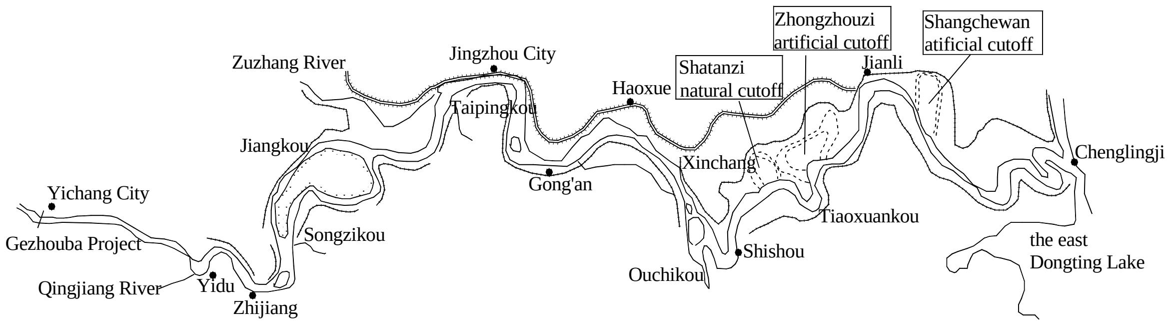


Fig. 2 Locations of Cutoff Works on Lower Jingjiang Stretch

With the cutoff works implemented, the Lower Jingjiang stretch was shortened by 78 km, accounting to 1/3 of its original total length. The river channel's curvature is decreased from the original 2.83 to 1.93, with increased river surface gradient and occurrence of retrogressive river bottom degradation, lowering water stage and increasing flood discharging capability there. Lower Jingjiang cutoff works also decrease flow diversion into Dongting lake and consequent outflow from Dongting lake as well as mitigation of restraint caused by Dongting lake outflow to Lower Jingjiang discharge. The process of sedimentation in Dongting lake slows down. Waterway length also shortened with elimination of 4 shoals. One word, obvious comprehension benefits in flood control, navigation and agriculture have been achieved.

3.2.3 Fork blockage works

The Yangtze stretches downstream of Chenglingji are braided channel stretches. Blockage works are implemented for those small lateral forks, the presence of which may have negative impact on dike safety and regime stability and whose blockage will not substantially raise upstream water level or not affect the river regime on its upstream and downstream. The blockage works that have been implemented during 1970s to 1990s include: Biandanzhou Right Fork, Yubanzhou Right Fork, Xijiang Fork, Xinglongzhou Left Fork, Taiyangzhou-Baishazhou Fork and Tuanjiesha-Congmingdao Fork.

The above blockage works are proved effective in improving river regime and navigation channel, eliminating bank collapse, developing the sedimentation islets, as well as eradicating oncomelania snails.

3.2.4 Integrated regulation works for key reaches

There are altogether 14 key reaches on the middle and lower Yangtze, where there are dikes on both banks protecting major cities and industries nearby. Their regime stability means a lot to the flood protection, water transport and socio-economic development. Since 1980s, 5 key reaches have been regulated in succession. The Phase I integrated regulation works for the reaches of Nanjing and Zhenyang were completed in 1993, while the Phase II is nearly being finished, both have seen initial effects on regime stabilization. In 2003, geotextile sand bags were dumped into the 60m deep river around Zhenyang Reach Hechangzhou Left Fork to form a 40m high underwater dam, effectively restraining the trend of drastic increase of flow diverted into this fork. Implementation of integrated regulation works for improvement of both flood control and navigation channel on Jiepai Reach of middle Yangtze provides an ideal solution to the conflict between flood control and navigation requirement. The first stage regulation works have also been executed for Lower Yangtze Ma'anshan and Anqing reaches in Anhui Province.

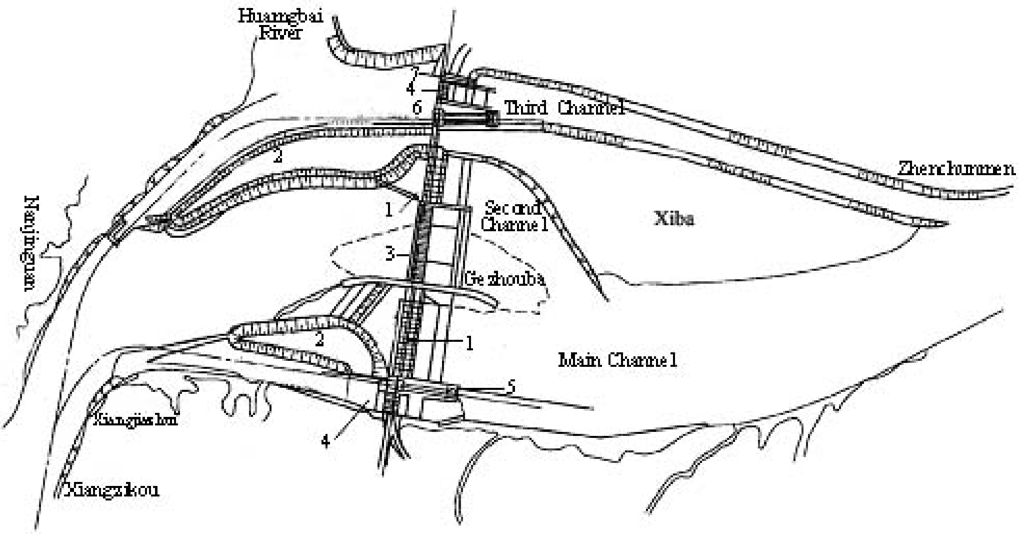
4 RESEARCH ON SEDIMENTATION RELATED TO MULTI-PURPOSE HYDROPOWER PROJECTS

In the past 50 years, a series of water resources and hydropower projects have been constructed in succession, including Danjiangkou, Gezhouba and Ertan, which have multiple benefits of flood control, power, navigation improvement and irrigation. Some other projects having the same benefit objectives are underway, such as TGP, Shuibuya and Zaoshi. Several others are in preparation stage, such as Xiluodu, Xiangjiaba and Tingzikou. The issue of sedimentation is closely associated with the reservoir lifespan, inundation scope of reservoir area, normal operation of waterway and ports in fluctuating backwater zone, operation of ship locks and power station, and impact of downstream scouring on flood control and navigation. Thus, sedimentation research is critical to project design and construction. Specific to sedimentation problems of each project, the approach of integrating prototype monitoring, mathematical modeling and physical modeling is adopted in the researches with a large amount of data derived, serving as the sound basis for project planning, design, implementation and operation.

CWRC started the researches on long-term operation of reservoirs from 1960s by on-site investigation to existing domestic reservoirs in North, Northeast and Northwest China as well as collecting relevant data of reservoir sedimentation all over the world. It is believed that the ultimate sedimentation of reservoir is tightly related to the way of reservoir operation. A majority of the effective storage can be maintained by means of a large drawdown of the pool level during flood season, with intensively sediment flushing along with flood release, and the recovery of pool level after flood season. Thereafter, the theory established for long-term operation of reservoir was applied widely in planning and operation of reservoirs built on Yangtze mainstream and tributaries, and helped to realize their maximum benefits.

Prototype investigation and monitoring data analysis as a whole, and field observation and measurement of Danjiangkou reservoir and its downstream channel in particular, gave birth to developments of 1-D and 2-D mathematical models of reservoir sedimentation calculation, downstream riverbed scouring calculation, combined calculation of scour and degradation of river channel and mainstream-connecting lakes. Physical models of sedimentation have been built to simulate the hydropower projects, backwater zone of reservoir, and downstream channels. All the modeling results have answered the questions as to water and sediment inflow, sedimentation in reservoir, at dam site and on downstream channels, etc., which were adopted in project design and verified by prototype monitoring.

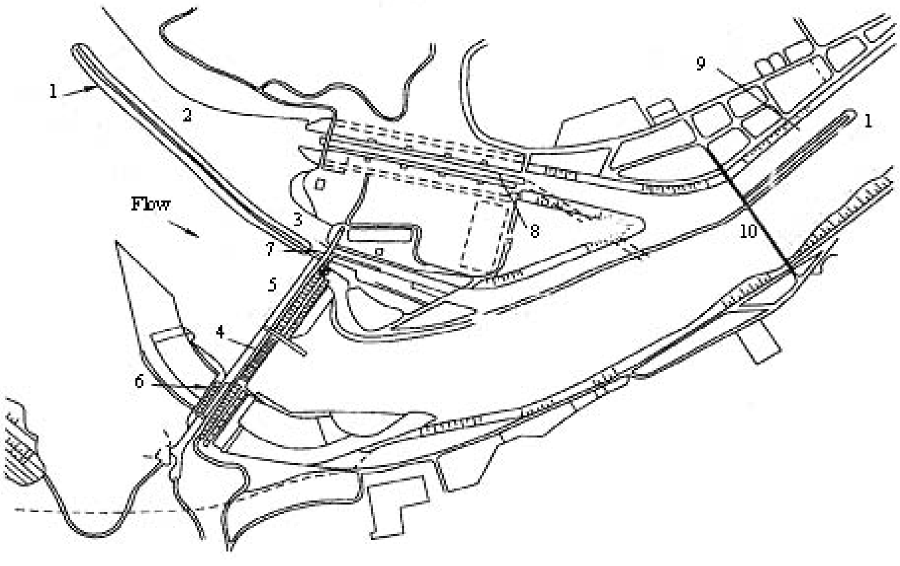
In the case of Gezhouba Project, the process to address its sedimentation issue includes prototype monitoring, analogue analysis with other existing projects of the same kind, and four physical models of dam site sedimentation. Based on these, the river regime planning was worked out for the dam site and consequently the overall layout of the Project was finalized (Fig. 3). The solutions comprise the measures of “still water for navigation, turbulent flow for sediment flushing” complemented with dredging, construction of silting-proof dikes and sediment flushing gate, solving the problem of flow condition and sedimentation on the approach channel of the shiplock; structural provisions for sediment training, trapping and bottom-outlet flushing, solving the problem of sediment prevention from the power station. 22 years of Gezhouba Dam operation justifies the sound layout and successful measures designed to address sedimentation.



1.Power Plant; 2.Depoisit-prevention Embankment; 3.Discharge Sluice; 4.Sediment Sluice; 5.Lock NO.1; 6.Lock NO.2; 7.Lock NO.3

Fig. 3 Overall Layout of Gezhouba Project

To find solutions to sedimentation problem of TGP, systematic researches are deployed, including studies on: reservoir sedimentation process, quantity and its mechanism; scour-deposition characteristics in backwater zone and its impact on flood control and navigation as well as countermeasures; relationship between reservoir operation mode and sedimentation; sedimentation in forebay and river regime readjustment mechanism; overall layout (Fig. 4); sedimentation and prevention/dredging measures on both upstream and downstream navigation approach channels; layout of bottom outlets for sediment discharging; downstream channel scouring process, quantity and change of river pattern, regime readjustment, river-lake relationship change. All these contribute scientific grounds to feasibility justification, structure design, construction, and future operation of TGP.



1.Deposit-prevention Embankment; 2.Upper Navigation Channel; 3.Ship Lift; 4.Spillway; 5.Left Power Plant; 6.Right Power Plant; 7.Sediment Sluice; 8.2-line and 5-step Lock; 9.Lower Navigation Channel; 10.The Xiling Changjiang Brige

Fig. 4 Overall layout of Three Gorges Project

Similarly, a significant amount of research finding have also been achieved for many other projects to address their sedimentation problems, including: Danjiangkou Dam on Hanjiang River; Wujiangdu and Goupitan Dams on Wujiang River; Geheyan, Shuipuya and Gaobazhou Dams on Qingjiang River; Jiangya and Zaoshi Dams on Lishui River; Wan'an Dam on Ganjiang River; Xiluodu and Xiangjiaba Dams on Jinshajiang Stretch of the Upper Yangtze; Tingzikou Dam on Jianling River, etc.

Sedimentation, from the technical perspective, is also one of the critical problems of the Middle-route of S-N Transfer Project. In the recent decade, in order to provide basic data needed for design, studies that have been carried include: impact of water transfer on Hanjiang River channel, by means of channel monitoring data analysis, mathematical and physical modeling; canal sedimentation; sedimentation related to river/canal crossing; impact of Yellow River crossing structure of the canal on Yellow River's flood control and regime.

5 KEY ISSUES PROPOSED FOR FURTHER STUDIES

Sedimentation issue is associated with flood control, navigation, water resources development and socio-economic development in the entire Yangtze Basin. Extensive researches on sedimentation have generated a wealth of findings, very conducive to the Yangtze development. However, due to the complexity and uncertainty pertaining to sedimentation, many key aspects are still in need of our continuing efforts for solutions.

(1) Soil erosion control and sediment resource utilization in an integrated way

The upper Yangtze Basin has been suffering severe soil loss, and currently 0.392 million km^2 of lands are eroded, added to which are additional 1,200 km^2 of erosion lands each year. The aggravating soil erosion not only is to blame for poverty and ecosystem deterioration, but also is the major contributor of sediments to Yangtze River. It also has strong impact on downstream flood control and the river-lake relationship changing process. An integrated approach needs to be studied to control the erosion. On the other hand, accumulation of sediment on riverbed will worsen the floods and result in near-shore scouring that endangers the stability of revetment and bank slopes. But sediment can also be taken as a sort of resource, which have wide range of applications. In the past, focus has been put on how to control and prevent sedimentation hazards, and little has been done to utilize it. Therefore, a comprehensive study is needed as to control soil erosion as well as to utilize sediment resource.

(2) Joint operation of reservoirs on both Yangtze mainstream and tributaries-impact and countermeasures

With socio-economic development and progress in West China Development strategy, as a number of reservoirs on upper Yangtze mainstream and tributaries as well as on middle and lower Yangtze tributaries have been in operation or in preparation of construction (e.g. Xiluodu, Xiangjiaba and Tingzikou) or under planning, the impact of all these reservoirs on sediment transport, river-lake interaction and its changes, flood control situation and ecosystem will be a long term and complex process, being imperative for further studies.

(3) Integrated regulation of lower Yangtze channels, lakes and estuary

The Three Gorges Reservoir and other water projects, once completed, will induce downstream changes in river and lake degradation and sedimentation, regime readjustment, and river-lake interrelation. Based on studies on these changes, in conjunction with economic development situation in the riverine areas, the planning on regulation of the middle and lower Yangtze channels, lakes and estuary needs to be revised and updated, with integrated regulation schemes worked out and implemented in a stepwise manner, so as to secure the sustainable socio-economic development.

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