UNESCO-ISI Online Training Workshop on Sediment Transport Measurement and Monitoring

Beijing, China, July 5-9, 2021

Lecture Note

Sediment Measurement for the Three Gorges Project

Guanglei DUAN

Sponsored by
UNESCO-IHP
Ministry of Water Resources, P.R. China
Organized by
UNESCO-IHP International Sediment Initiative (ISI)
International Research and Training Center on Erosion and Sedimentation (IRTCES)
China Institute of Water Resources and Hydropower Research (IWHR)
UNESCO Beijing Office
Co-sponsored by
World Association for Sedimentation and Erosion Research (WASER)
International Association for Hydro-Environment Engineering and Research (IAHR)
Jingjiang Bureau of Hydrology and Water Resources Survey

Sediment Measurement for the Three Gorges Project

Guanglei DUAN
Jingjiang Bureau of Hydrology and Water Resources Survey, Changjiang Water Resources Commission, Jingzhou 434000,China;cjwjjjdgl@163.com

ABSTRACT

Sediment problem is one of the key factors which affect the dispatching operation and life of the Three Gorges Project (TGP). Many approaches were employed to research the sediment problems of the TGP during its demonstration, planning, design, construction and operation, and many important results were obtained. In order to help participants from all over the world to understand the progress of hydrologic sediment measurement in China's representative projects and the experience of sediment observation in super large reservoirs，according to requirements of the training course, the flow and sediment measurement of the Three Gorges Project is mainly introduced in this paper in combination with the author's long-term work on hydrological and sediment observation. It includes the general situation of TGP, the distribution of the hydrological network, the measurement factors, observation technologies and the sediment changes in the reservoir and downstream after the impoundment of TGP. The 18-year operation of TGP shows that the basic situation of sediment problems is good, and the local problems were or are in control through proper treatment. However, these sediment problems can probably accumulate, develop and transform with time, so they should be paid continuous attention.

1. BRIEF INTRODUCTION OF THE THREE GORGES PROJECT

Yangtze River is the longest river in the People's Republic of China, and is one of the longest in the world. The total length of Yangtze River is over 6300 km. It ranks the third in the world, only shorter than the Nile and Amazon.

The section above Yichang is the upper reaches with a length of 4504 km and drainage area of 1 million km^2 the one from Yichang to Hukou (connection of Poyang Lake to the River) is the middle reaches with a length of 955 km and drainage area of 680,000 km^2; and below Hukou is the lower reaches with a length of 938 km and drainage area of 120,000 km^2. The total drainage area of Yangtze River is 1.8 million km^2 covering 19 provinces and cities.

A lot of areas suffered flood in Yangtze River valley. In mountain areas of the upper reaches and branches, there are such disasters as landslide, landslip and mud-rock flow caused by flood and rainstorm. In plains of middle and lower reaches, flood often occurs overflowing riverbed. According to historical record, there are 214 floods from Han Dynasty, 185 B.C., to late Qing Dynasty, 1911, about once every 10 years. Yangtze River is the one with the most developed inland navigation. As a key part of the flood control system in the middle and lower reaches of the Yangtze River, the Three Gorges Project controls 96 percent of the inflow to Jingjiang, the most dangerous river section during floods, and over two-thirds of the inflow to Wuhan.

The Three Gorges Project is the key project for the development of Yangtze River Basin. The

Three Gorges Dam is a concrete gravity dam. Its length is 2335m, width is 115m at bottom, 40m on top and height is 185m.The normal impounded water level is175 m. The total storage capacity is 39.3 billion m^3. The flood control capacity is 22.15 billion m^3. The adjustment capacity is seasonally adjusted. The Hydropower Stations is 32 700000-kw-generating units, in which there are 14 at left bank, 12 at right bank and 6 underground. In addition, there are two 50,000-kw power generating units.

The Three Gorges Reservoir has retained an accumulative total of 153.3 billion cubic meters of flood water inflow from 2003 to 2019 and plays an indispensable role in mitigating the floods and in reducing the massive floods in the upper reaches of the Yangtze River.

The mainstream has always been called "Gold Waterway". The massive project has also played a significant role in improving navigation conditions and increasing shipping capacity in China's Yangtze River. Since the Three Gorges Reservoir started impounding in 2003, cargo transport condition has significantly improved. At the same time, the transportation costs have been greatly lowered as the average energy consumption of ships reduced to a third of what it was prior to the Three Gorges Project. The Three Gorges Dam commissioned a double-way five-step ship lock in 2003, which has since operated for 17 years consecutively by 2020. It has handled 875,300 ships and shipped 1.47 billion tons of freight. Total freight cargo volume for 2019 was 146 million tons, 46 percent above the design capacity and 8 times more than the maximum freight capacity at the river section before the impoundment of Three Gorges Reservoir. The Three Gorges ship lift launched trial navigation on September 18, 2016. By June 2020, the ship lift has handled 10,000 ships with 360,000 passengers, cutting down the time it takes to pass the dam to around 40 minutes.

One hundred years ago, Dr. Sun Yat-Sen, the great forerunner of China's democratic revolution, raised the idea of exploiting the water and hydro-electric resources of the Three Gorges. After the founding of New China, Comrade Mao Zedong, Comrade Deng Xiaoping and other proletarian revolutionaries gave a great deal of their time and thought to the proposed Three Gorges Project. Several generations of Chinese scientists have put in an enormous amount of hard intellectual work.

On April 3, 1992, the Fifth Session of the Seventh National People's Congress Adopted the Resolution on the Construction of the Three Gorges Project on the Yangtze River.

On December 14, 1994, Premier Li Peng of the State Council announced at the commencement ceremony of the Three Gorges Project held in Sandouping, Yichang that the Three Gorges Project was officially started.

On November 8, 1997, the Three Gorges Project realized the closure of the main river, marking the successful completion of the five-year first phase of the project and the transfer of the project to the second phase.

On June 1, 2003, the Three Gorges Project officially impoundment.

On June 16, 2003, the Three Gorges Ship Lock began its trial operation. The Three Gorges Project has four main benefits, namely, flood control, power generation, navigation and water resources utilization, among which flood control is considered to be the most core benefit of the Three Gorges Project. Impoundment process of Three Gorges Reservoir is marked on Figure 1.1.

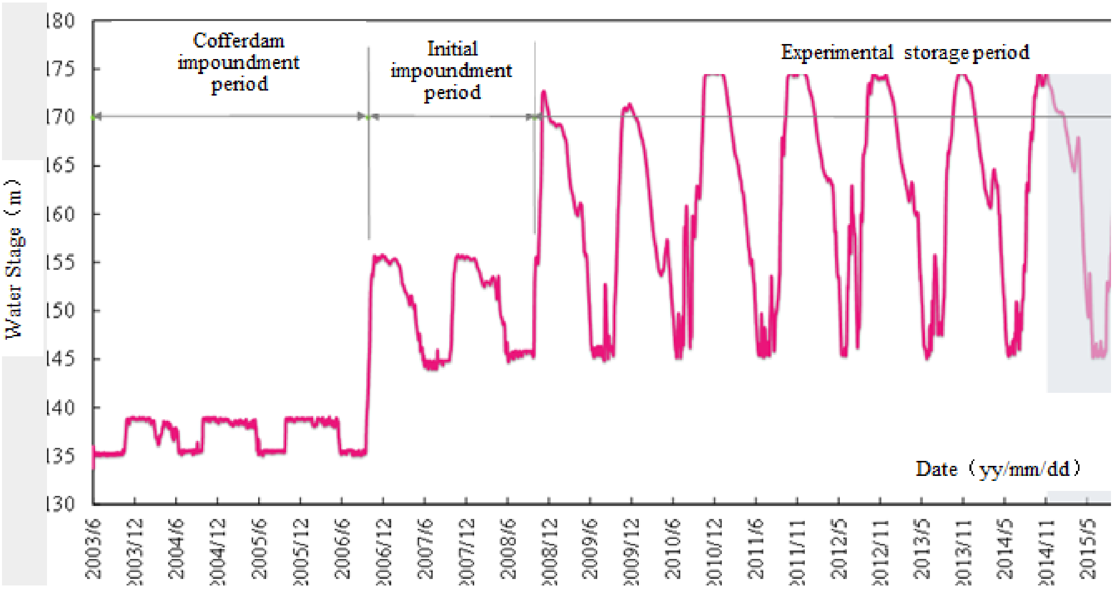


Fig. 1.1 Impoundment process of Three Gorges Reservoir

2. DISTRIBUTION OF HYDROLOGY STATIONS AND MEASUREMENT SYSTEM

In order to collect basic data and to provide services for basin engineering construction, the Changjiang Water Resources Commission has gradually established a large number of hydrology stations along the main stream and tributaries of the Yangtze River since the 1950s. By the 1990s, a complete network of hydrological and sediment monitoring network had been basically formed. It includes 118 hydrological stations and more than 200 water level stations along the main stream and key tributaries of the Yangtze River basin. In addition, a large number of river survey and sediment analysis have been completed. The hydrological and sediment observation data of the past decades by us for several generations provided scientific basis for the demonstration, design, construction and operation of the Three Gorges Project. See Figure 2.1.

The prototype observation is executed to serve the sediment research, construction and operation of TGP in the different period. After the reservoir began its storage in 2003, the sediment issue appears both in upper and lower reaches, thus the observation goal becomes more clear, and the prototype observation and corresponding sediment research are executed to serve operation of TGP directly. The observation goal includes the following aspects: Mastering the background data of natural channel status before impounding completely; Making reference for the decision of installment impounding plan; Real time monitoring of the variation of erosion and deposition both in upper and lower reaches after impounding, and finding out the problems, so as to take countermeasure in time; Validating the simulation technology adopted, and increasing the credibility of TGP sediment forecasting.

The hydrological sediment prototype observation range includes the reservoir area, dam site and lower reaches. Since 1949, based on long time's sediment measure, channel observation and exploration and investigation, lots of prototype observation data and analysis research results had been accumulated, thus meet the demand of planning, design and scientific research in definition phase. The construction phase is an interim to succeed the prophase, and the total period of construction is 17 years, so variation information of runoff, sediment and boundary condition must be observed continuously to provide dependence not only for design, scientific research, construction and operation, but also for validation and optimization of design and regulation.

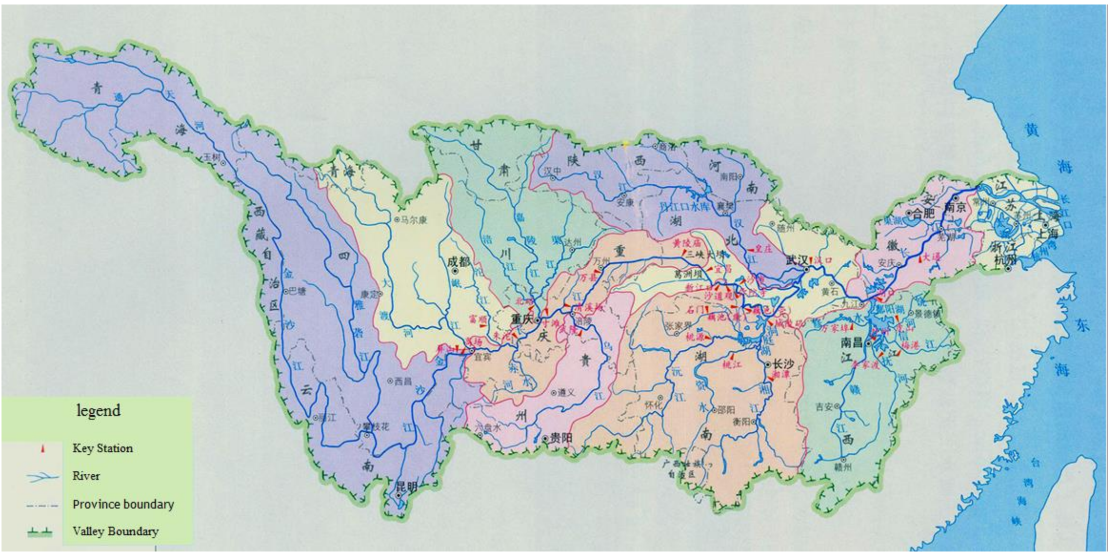


Fig.2.1 Distribution of key hydrological stations along main stream and tributary

The monitoring factors mainly include hydrology, sediment and channel terrain. The channel terrain survey is mainly to get the regularity of evolution of channel in the raw, the sediment deposition at the reservoir, erosion downstream and evolution of the key reaches after the impoundment of the TGP. See Figure 2.2.

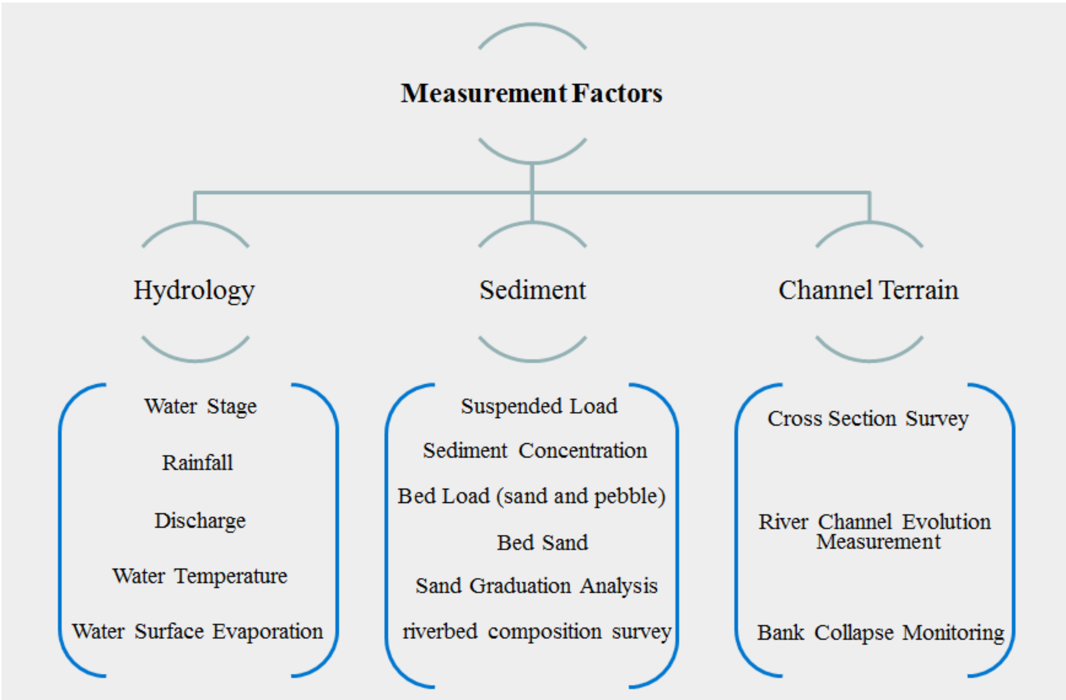


Fig. 2.2 Measurement system

3 MEASUREMENT TECHNOLOGIES OF FLOW AND SEDIMENT

3.1 Water Stage

Before 1990s, it was mainly by artificial watching and float type level meter to get water level data. After1990s, the pressure-type water level gauge and non-contact ultrasonic water level gauge are mainly used for automatic observation. The staff gauge serves as auxiliary calibration function. Twenty years ago, water level automatic recording, transmission and storage were basically realized in the Yangtze River. See Figure 3.1-1 to Figure 3.1-4.

Fig.3.1-1 Check water gauges

Fig.3.1-2 Pressure-type gauge

Fig.3.1-3 Radar-type water gauge

Fig. 3.1-4 Bubble-type gauge

3.2 Rainfall

Many kinds of automatic rain gauges are used for rainfall observation. It can record, transfer and store data automatically. Before the flood season every year, the water injection test must be finished in order to check the instrument. See Figure 3.2.

Fig. 3.2 Automatic pluviometer and water injection test

3.3 Discharge

Twenty years ago, the discharge observation was mainly using the current meter method at the vertical points. Now current meter carried by cableway and Horizontal ADCP are widely used in the small rivers. The Acoustic Doppler Current Profilers (ADCP) carried by ship is widely used in large river. The method of Acoustic Doppler Current Profilers carried by ship is equipped with GPS and electronic compass. At present, many non-contact surface velocity measuring instruments are being tested, such as side-scan radar, airborne radio current meter, digital particle image velocimetry, etc. If we can get best the relationship between the apart surface velocity and the cross-section velocity, obtaining the discharge value is become so easy. The discharge on-line monitoring can be realized. See Figure 3.3-1 to Figure 3.3-5.

Influenced by water conservancy projects, the hydrological measurement condition in natural rivers changed greatly. To obtain the complete hydrological factor variation process would increase the measurement times and result in the increment of workload and cost. Using on-line H-ADCP discharge measurement is an effective way to measure the discharge in the river channels influenced by water conservancy projects. H-ADCP can realize real-time online monitoring of discharge. The relationship between the representative velocity of H-ADCP and the average velocity had significant effect on the accuracy of discharge monitoring. H- ADCP is one of the most commonly used hydrological automatic flow detection equipment, and has been widely used in hydrological systems. The calibration of flow velocity relationship has always been the key technology in the application of H-ADCP. The traditional calibration method of H-ADCP is to establish the relationship between the representative flow velocity and the average cross-section flow velocity by manual lead fish or shipping ADCP.

The particle image velocimetry (PIV) is an effective and non-intrusive technique to measure the planar distribution of velocity in the fluid based on the cross-correlation of flow images. The DPIV (Digital Particle Image Velocimetry) is a kind of method to obtain velocity fields quickly. It is a new measurement technology in the field of hydrology. The advanced image processing technology is applied to analyze the river surface texture image to obtain the surface texture features and the movement data and distribution of the tracer.

Particle Image Velocimetry (PIV) is recognized as the most powerful and practical diagnostic tools for flow field analysis in fluid dynamics applications. Instantaneous 2D and 3D flow images are measured with high spatial and temporal resolution. The experimental setup of a PIV system typically consists of several subsystems. In most applications tracer particles have to be added to the flow. These particles have to be illuminated in a plane of the flow at least twice within a short time interval. The light scattered by the particles has to be recorded either on a single frame or on a sequence of frames. The displacement of the particle images between the light pulses has to be determined through evaluation of the PIV recordings. In order to be able to handle the great amount of data which can be collected employing the PIV technique, sophisticated post-processing is required. See Figure 3.3-6.

The electronic buoy uses GNSS technology to track the trajectory, velocity and direction of water. By analyzing these data, the river flow pattern can be obtained. The electronic buoy has been successfully used in Yangtze River, Hanjiang River and other rivers. See Figure 3.3-7.

The automatic cable flow measuring robot system employs non-contact radar wave velocity meter as the surface velocity measurement sensor, uses the simple double-track cable to move the radar wave flow measurement meter to the above of the flow measuring position for measuring the surface flow velocity. At the same time, the system can collect real-time water level data to realize automatic monitoring the level and flow. The system can automatically control the whole process of flow measurement, with strong error control ability and good auxiliary management ability, which solves the problem of automatic flow measurement of small and medium-sized rivers and rivers of sharply flow rising and falling in mountainous areas. See Figure 3.3-8.

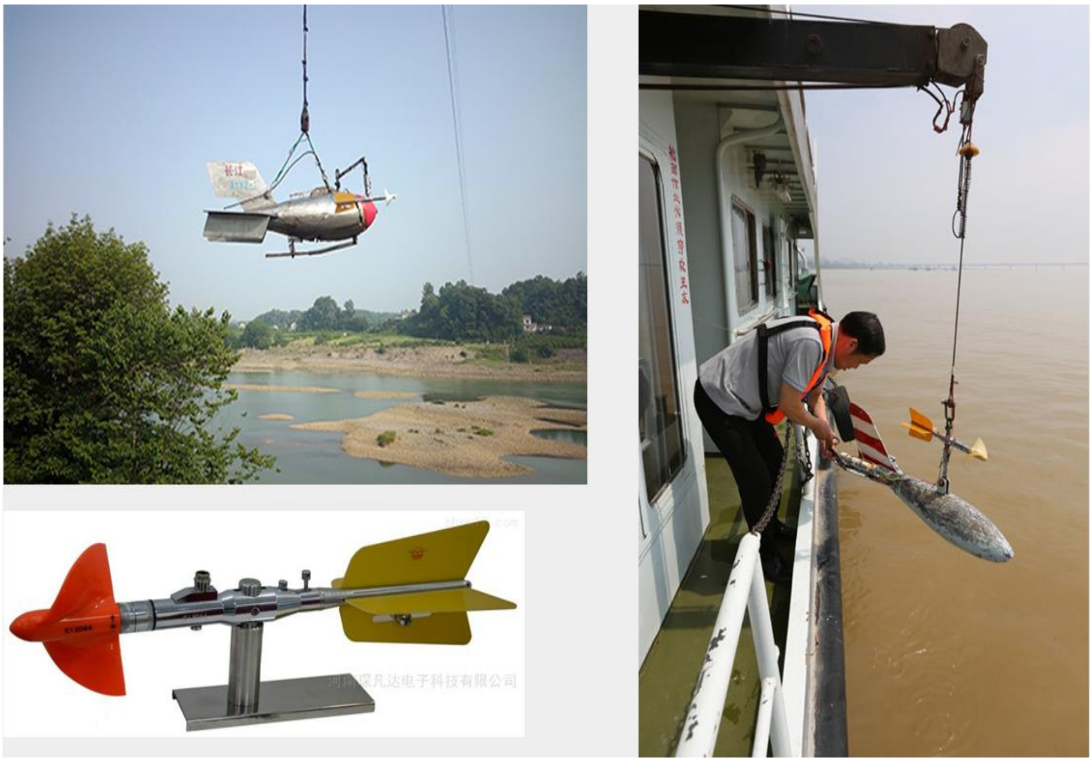


Fig.3.3-1 Current meter carried by cableway and ship

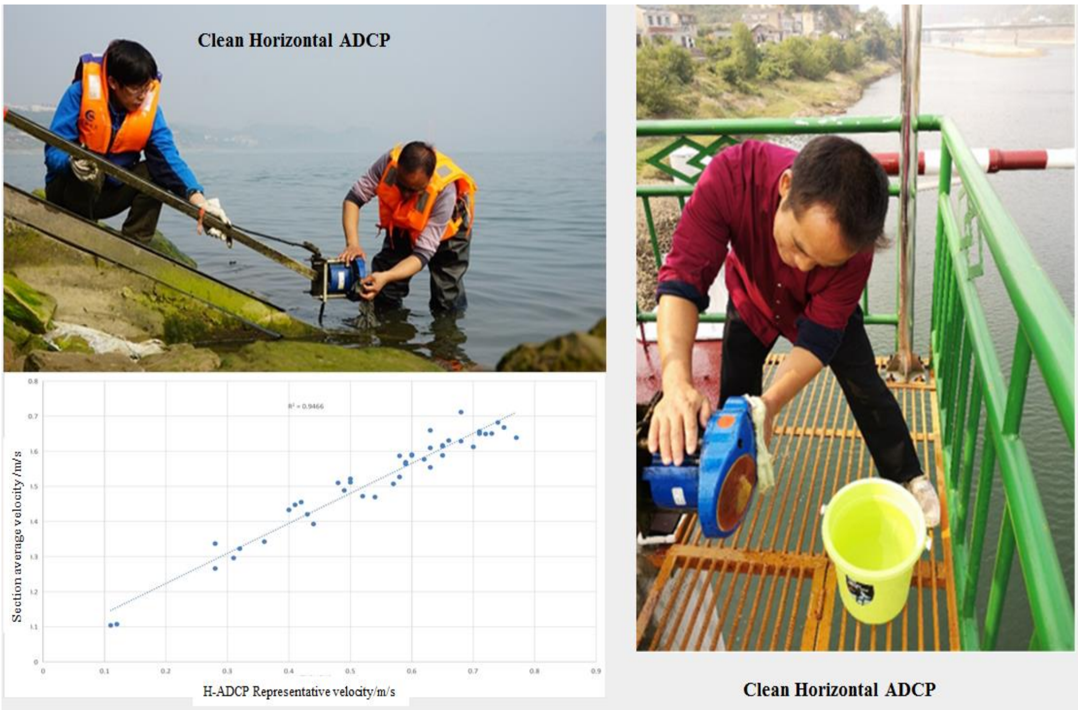


Fig. 3.3-2 H-ADCP- Acoustic Doppler Current Profilers (online)

Fig. 3.3-3 ADCP- Acoustic Doppler Current Profilers carried by ship

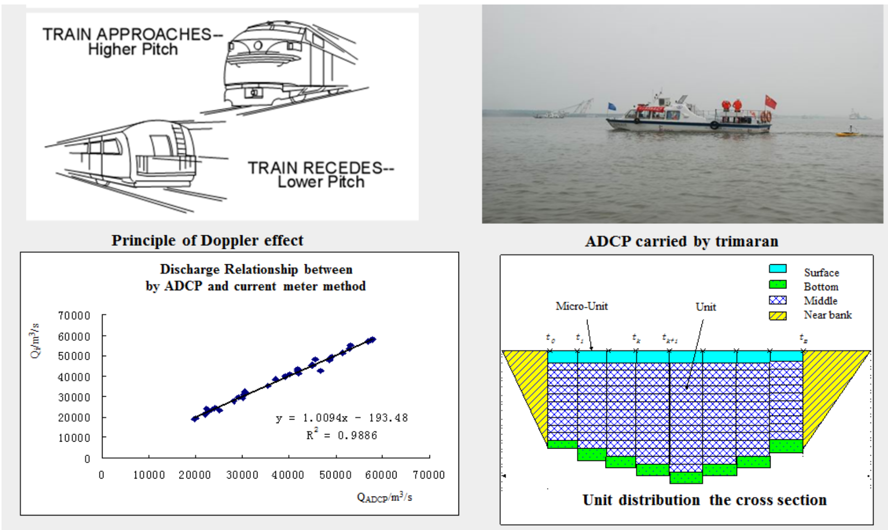


Fig. 3.3-4 Principle of ADCP and result of comparative test with conventional approach

Fig. 3.3-5 Different non-contact surface velocity measuring instruments

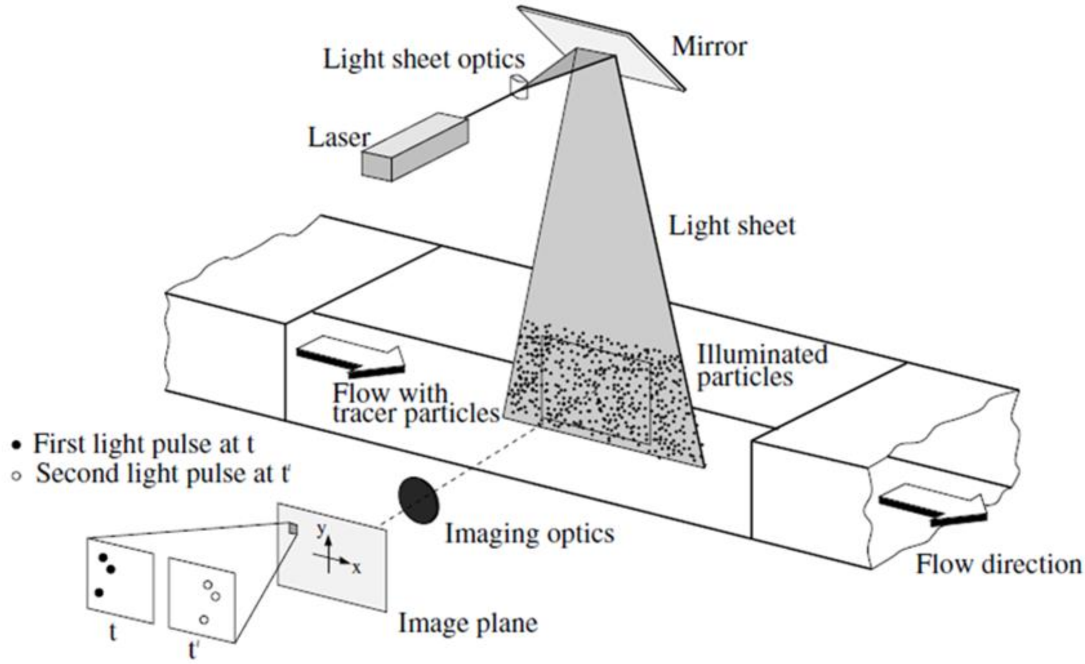


Fig. 3.3-6 PIV System

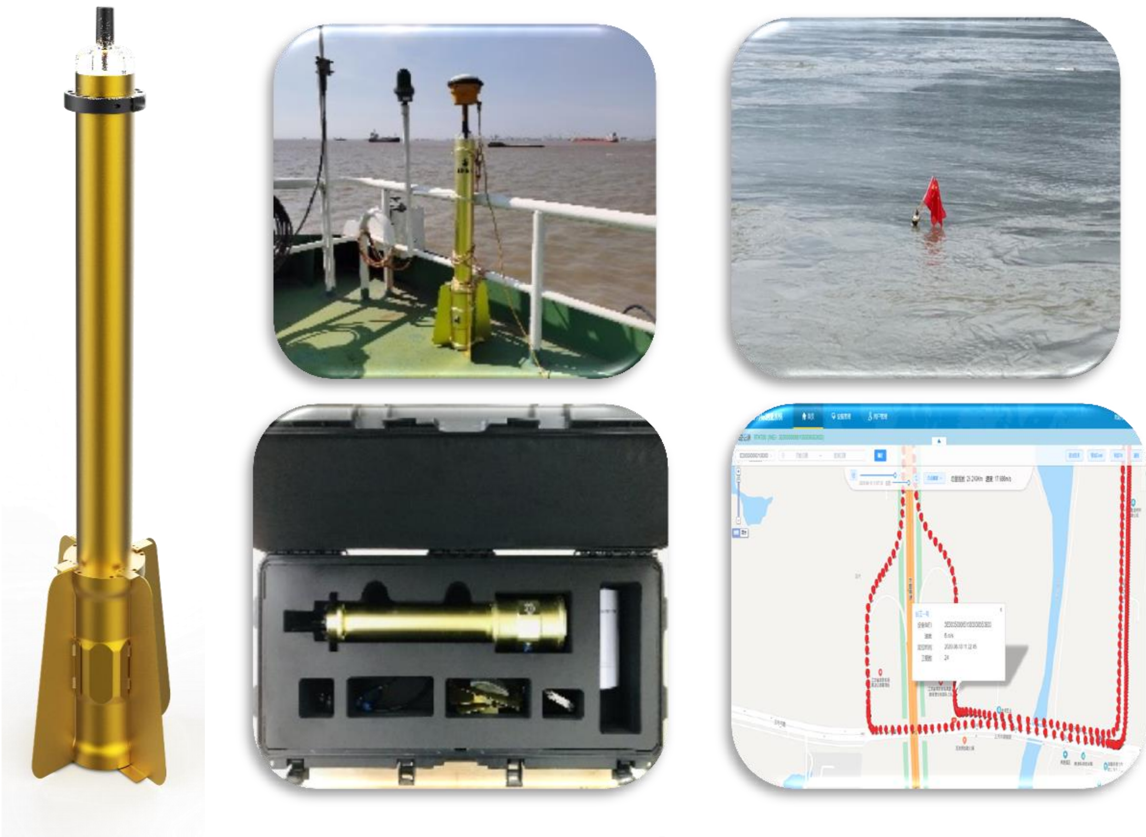


Fig. 3.3-7 Electronic Buoy

Fig.3.3-8 Automatic cable flow measuring robot system in hydrologic station

3.4 Sediment

The suspended sediment sampleis collected by horizontal type sampler or time-integrated type suspended sediment sampler carried by cableway. We also can get the suspended sediment concentration quickly using the turbidimeter and collect the bed material using prod-type sampler. In order to collect the suspended sediment near the river bed, we invented multi-compartments sampler. Before using, comparative test between turbidimeter and conventional approach in different flow condition must be finished and the result must require the code. See Figure 3.4-1 to Figure 3.4-4.

There are several main methods for bed material sampling，such as digging bucket type, plough type and bevel-type. Roller type, spinner handle type, piston drill pipe type, rotary type and plank type are frequently-used for sediment-dry bulk density sampler. See Figure 3.4-5 to Figure 3.4-8.

The sediment concentration is an important content in the collection of hydrological basic data. The traditional method of drying and weighting after collecting water sample cannot meet the timeliness requirements today. Based on Mie scattering principle, a method of measuring sediment concentration by laser particle size analyzer was proposed in practice. The volume concentration of suspended sediment particle size distribution in water samples with certain suspended sediment content was analyzed by laser particle size analyzer. The conversion relationship between volume concentration and weight concentration was calibrated. The suspended sediment content can be converted rapidly when the distribution of suspended sediment particle size was analyzed. See Figure 3.4-9and Figure 3.4-10.

Analytical method of sediment particle gradation includes sedimentation velocity method, screen classification, photoelectric particle analyzer and Malvern laser particle size analyzer. The laser method has been widely used in the hydrological system of the Yangtze River Basin. See Figure 3.4-9 and Figure 3.4-10.On line monitoring of sediment concentration has been implemented in Zhicheng Hydrological Station.

Fig.3.4-1 Time-integrated type suspended sediment sampler carried by cableway

Fig.3.4-2 Multi-compartments sampler

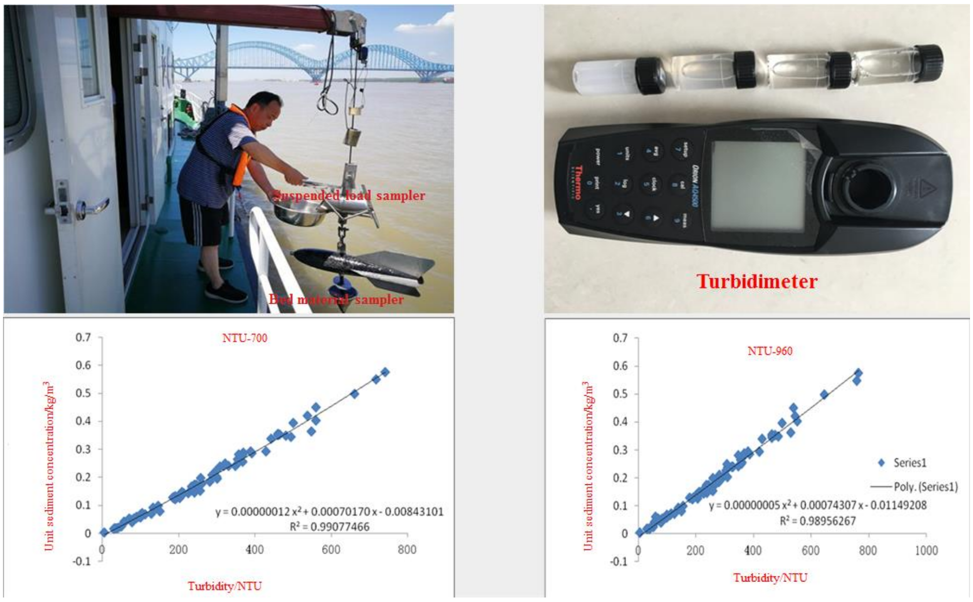


Fig. 3.4-3 Horizontal type sampler and turbidimeter

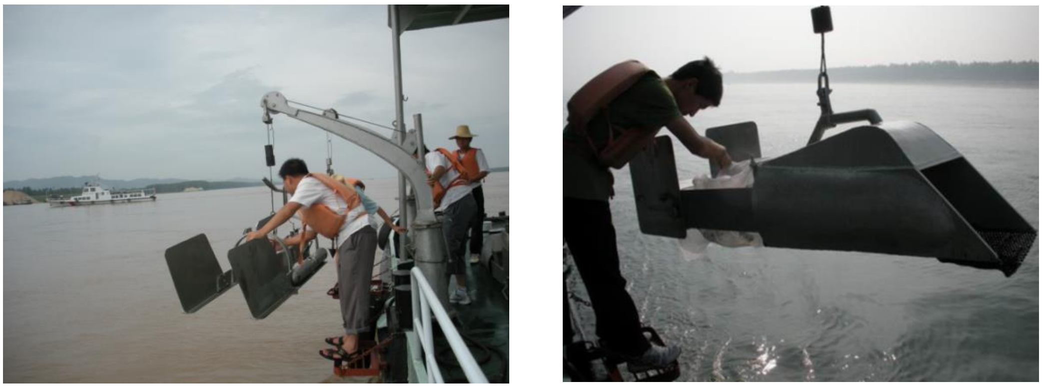


Fig. 3.4-4 Bed load sampler: sand (left), pebble (right)

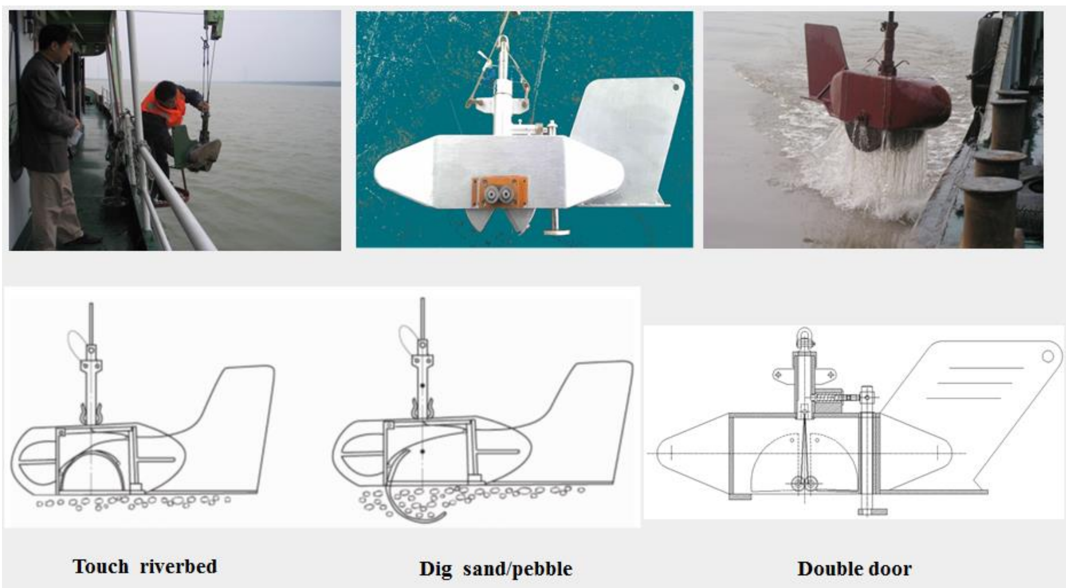


Fig. 3.4-5 Bed material sampler: Digging bucket type

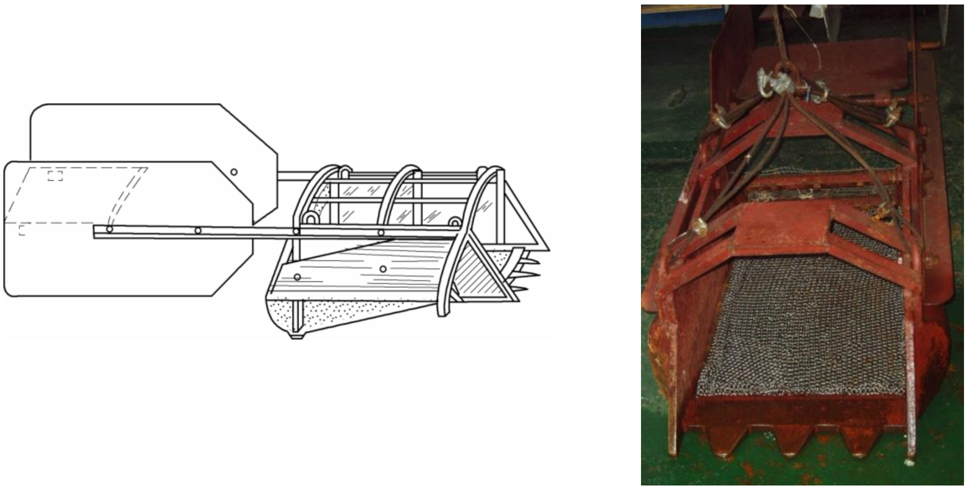


Fig. 3.4-6 Bed material sampler: Plough type

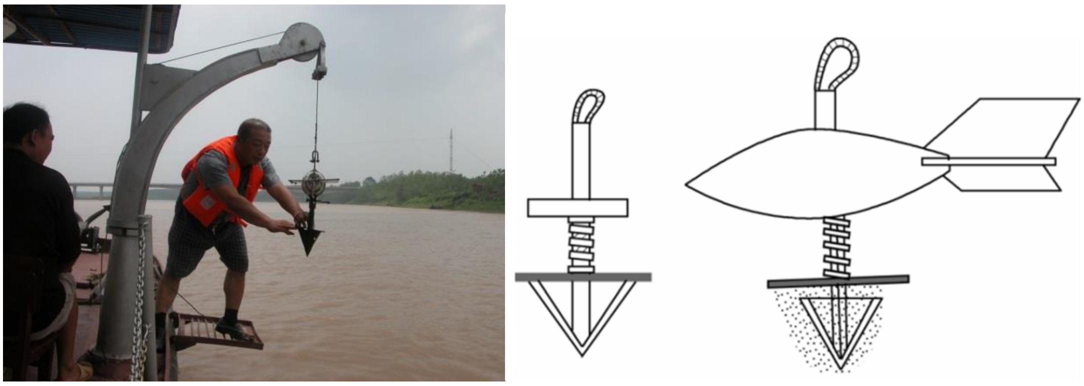
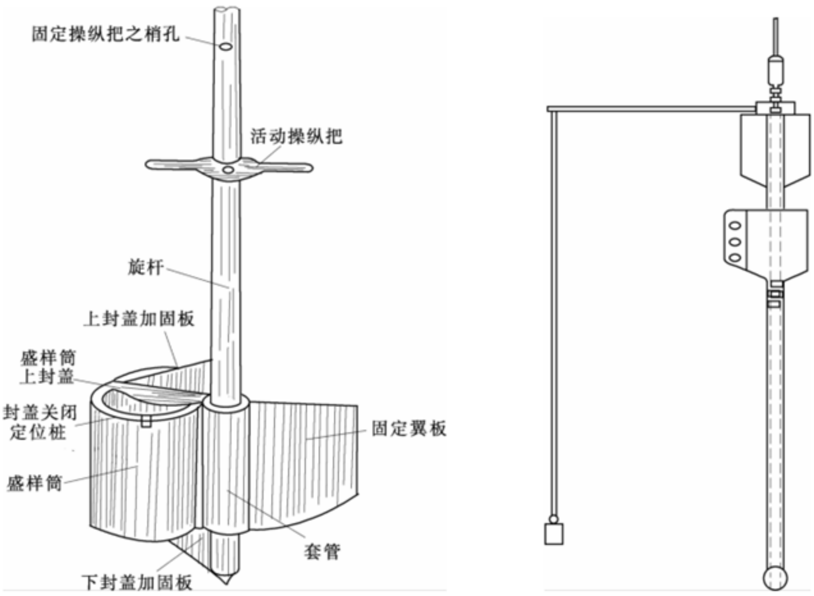


Fig. 3.4-7 Bed material sampler: Bevel-type



Spinner handle type **Piston drill pipe type**

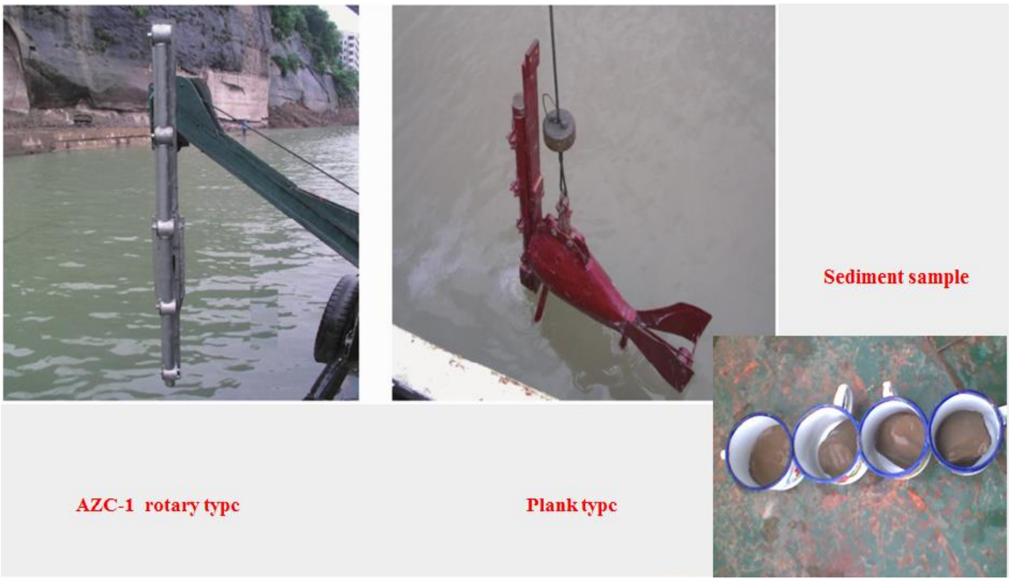


Fig. 3.4-8 Sediment-dry bulk density sampler

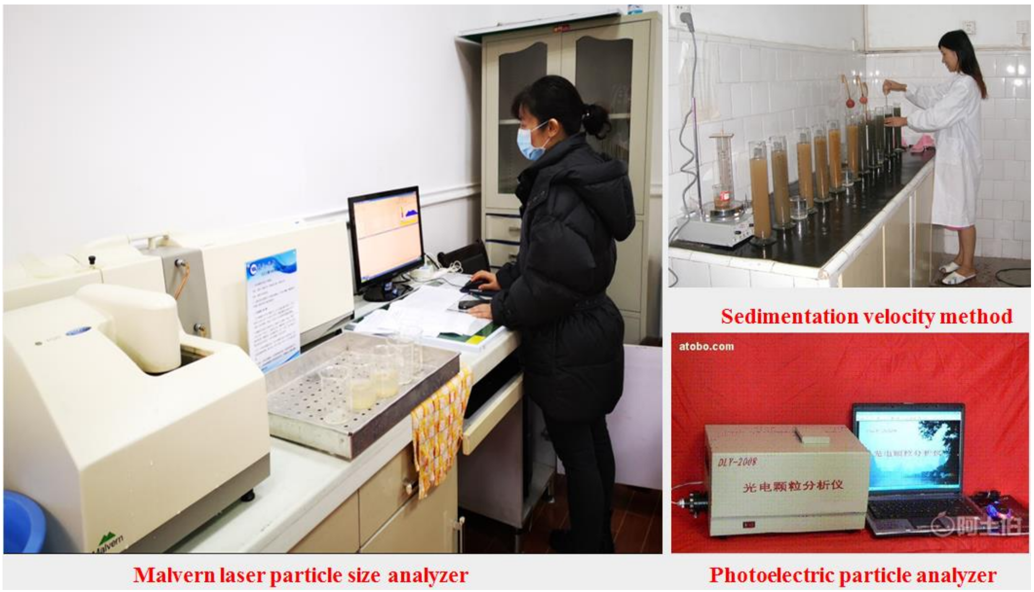


Fig. 3.4-9 Different analytical method of sediment particle gradation

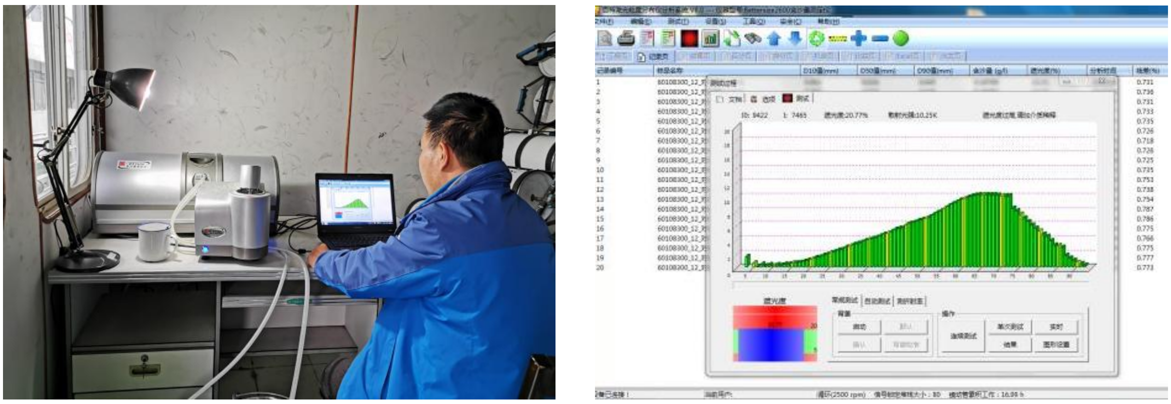


Fig. 3.4-10 Baite 2600 laser particle size analyzer

3.5 Water surface evaporation

Water surface evaporation observation is using the automatic evaporator of water surface. See Figure 3.5.

Fig.3.5 Automatic evaporator of water surface

3.6 Topographic survey

In order to know the sediment deposition in the reservoir, erosion downstream and the evolution of key reaches, channel survey is carried out at regular intervals. Underwater topographic survey and fixed section survey adopts GPS positioning coordinates, single beam or multiple beams to measure water depth. See Figure 3.6-1 to Figure 3.6-2.

Land topography survey adopts GPS plus RTK, 3D laser scanning measure system carried by aircraft or onboard, at land. See Figure 3.6-3. 3D laser scanning technology can obtain spatial data quickly and accurately by incorporating light, electricity and computer technology.

Through computer technology, automation technology and modern surveying and mapping technology, an underwater landform surveying vessel system was studied and developed by integrating unmanned vessel, GPS, echo sounder, obstacle avoidance radar, wireless communication equipment, computer, electronic compass, power system and other equipment.

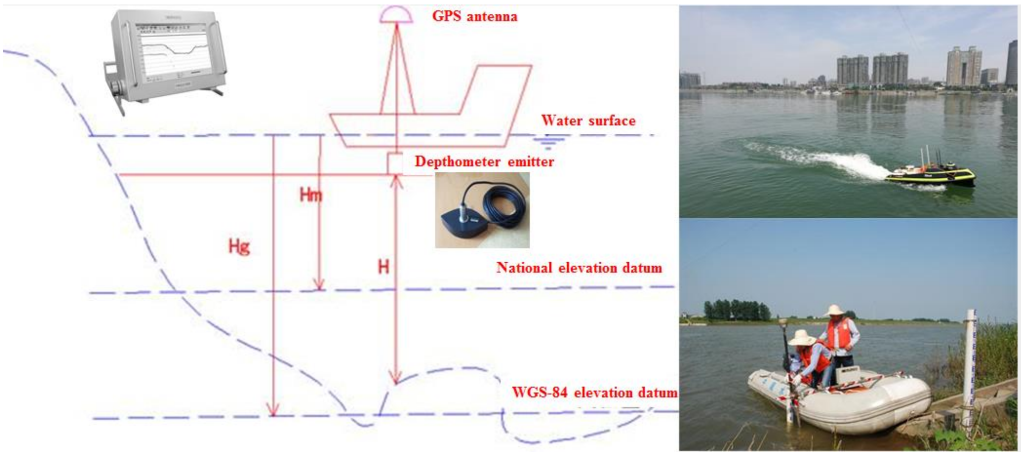


Fig. 3.6-1 Principle of underwater topographic survey (Single beam)

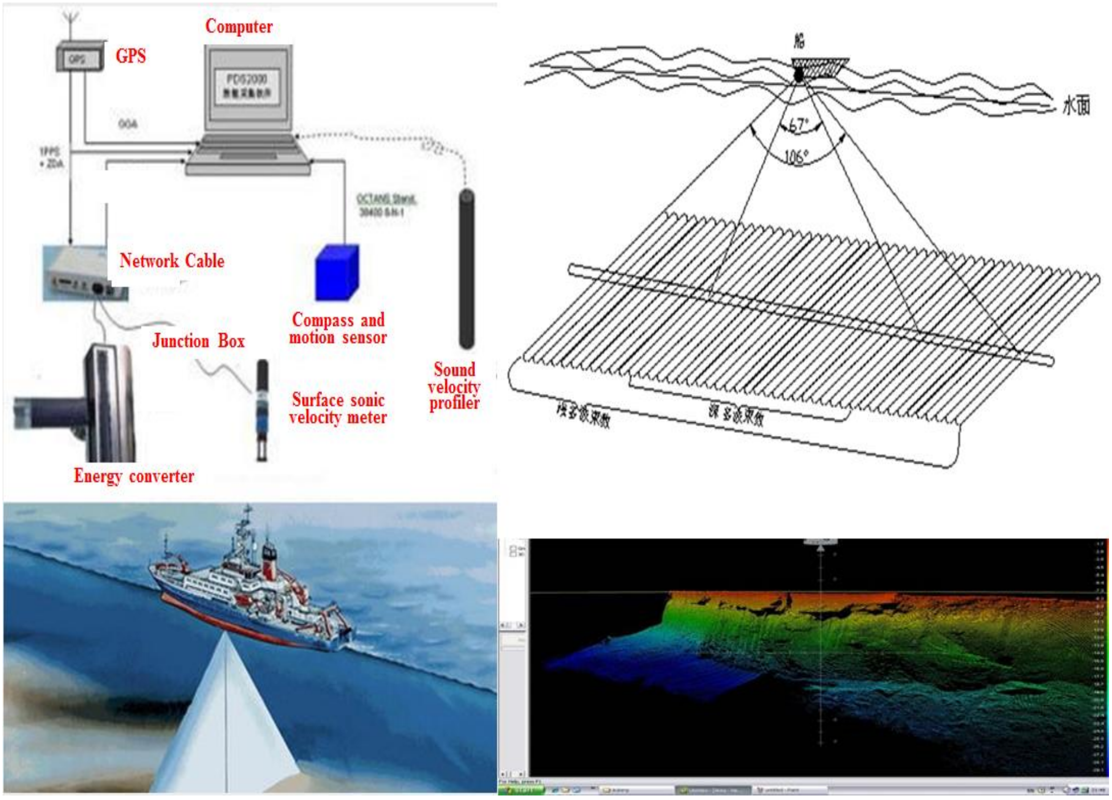


Fig. 3.6-2 Principle of underwater topographic survey (Multi-beam sounding system)

Fig. 3.6-3a Different methods of land topography survey

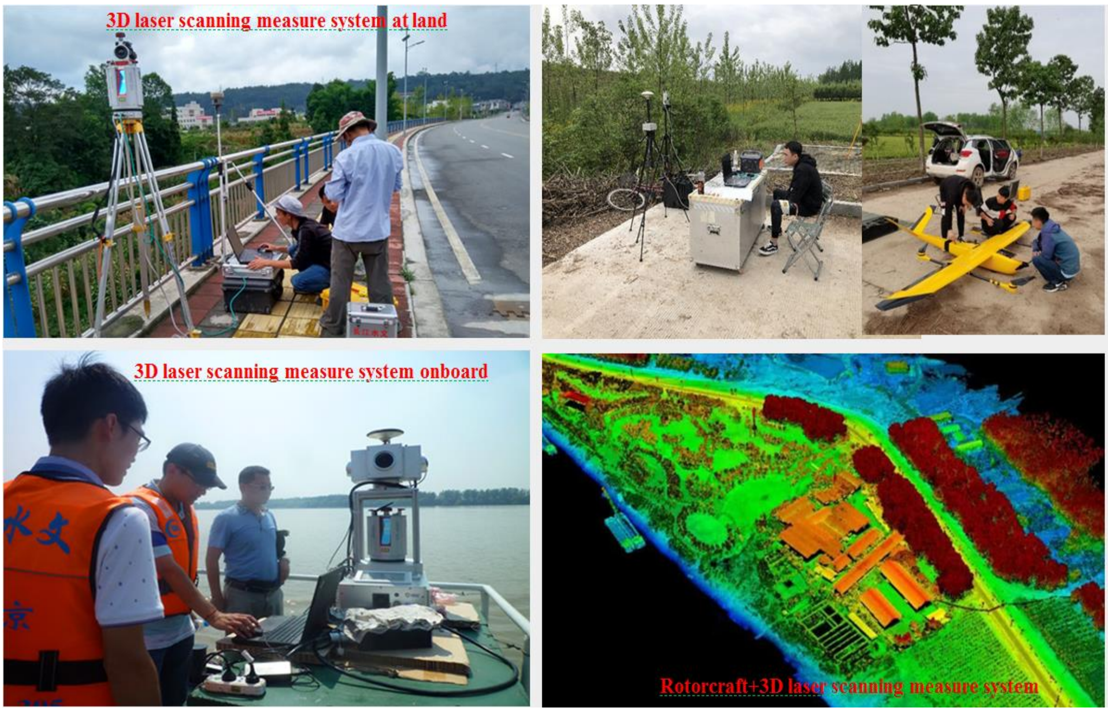


Fig. 3.6-3b Different methods of land topography survey

4 SEDIMENT MEASUREMENT RESULTS

4.1 Changes of inflow and outflow runoff and sediment of Three Gorges Reservoir before and after the impoundment

The runoff of TGP reduced slightly, and the sediment continued to decrease obviously from 1991 because of dam construction, soil and water conservation, sand excavation, distribution of rain, etc. About 76% sediment deposited in the Tree Gorges Reservoir. The reservoir sediment deposition rate is far less than the design value. Sediment deposition in the reservoir area is mainly located in the main channel of the original channel. The bed longitudinal section rose obviously after few years since impoundment. See Figure 4.1-1 to Figure 4.1-5.

The silt problem is one of the key technical problems in the Three Gorges Project. In the demonstration and preliminary design phases of the Three Gorges Project, adoption of the "storing clean water and discharging muddy flow" method was proposed for solving the silt problem. The implementation of reservoir water impoundment in 2003 showed that the reservoir generally follows "storing clean water and discharging muddy flow" scheduling principle and its mode of operation is optimized based on new conditions such as the reduction of upstream water and silt.

Sedimentation and sediment delivery in the Three Gorges Reservoir (TGR) has always been a hot issue during its demonstration and operation. The result demonstrates that despite rare changes in annual runoff, the total amount of sediment load transport into the TGR shows a significant reducing trend (by 60%) after the impoundment of the TGR. Analysis of the field data shows that the average sediment delivery ratio of the TGR is 24% during 2003-2018 and the annual loss in storage capacity is about 0.3%. Annual sedimentation is in a linear relation with incoming sediment, and the slope of the relation is larger when water level gets higher in flood season. Sediment mainly deposits in river reaches with wide cross sections, especially in the permanent backwater area where the flow velocity is relatively small. In some branching reaches, the river pattern develops towards unification.

The measurement results indicated that there are three important influencing factors to the sediment diversion ratio, one is the riverbed character of the reservoir area, the other is the flow and sediment condition, and the third is the water level before dam. From June 2003 to December 2010, the sediment diversion ratio is 26.1%. The sediment discharging centers from May to October each year, during which the sediment diversion ratio is about 29.0%, especially during the flood peak time, the velocity is large, and the flow has a strong sediment transportation ability, the sediment diversion ratio is high, when the inflow discharge is larger than 30000m3/s, the highest sediment diversion ratio is 81.0%.With the rise up of the water level before dam, the sediment diversion ratio decreased, especially the capacity of coarse particle, to some extent, it affects the sediment diversion ratio, the sediment transport ability decreases with the decreasing of the flow velocity, accordingly, the sediment diversion ratio of the coarse particle decreases more evident than the total load with the decreasing of the flow velocity.

The comparison results shows that the upstream flow and sediment into the reservoir reduce and are basically in accordance with prediction in design stage, but the time for reduction is ahead of the predicted; then sedimentation in the reservoir is far below the predicted results; the scouring in the downstream is basically in accordance with the predicted, but the scoured range is larger than the predicted; the impact of the scouring in the downstream on the flood control and navigation is basically in accordance with the predicted; in general, the sediment issues of the TGP are within the predicted scope in initial design stage.

Since the operation of the TGP, sediment deposition occurred primarily at the wide and curved reaches in the permanent backwater region, while no deposition occurred at the gorge reaches. The sediment carrying capacities decreased gradually due to the rising of the water level after the impoundment, and the deposition ratio increased step by step. The sediment carrying capacities at the wide reaches reduced greatly to the values smaller than the sediment concentrations, thus deposition occurred. While the reduction of the sediment carrying capacities at gorges was relatively small, and the sediment capacities were still bigger than sediment concentrations, no cumulative deposition happened consequently. The bigger the flow discharges, the smaller the sediment carrying capacities at the wide reaches were than the sediment concentrations, but the opposite at the gorge reaches, demonstrating that deposition at the wide reaches occurred mostly during the flood season and erosion occurred at gorges.

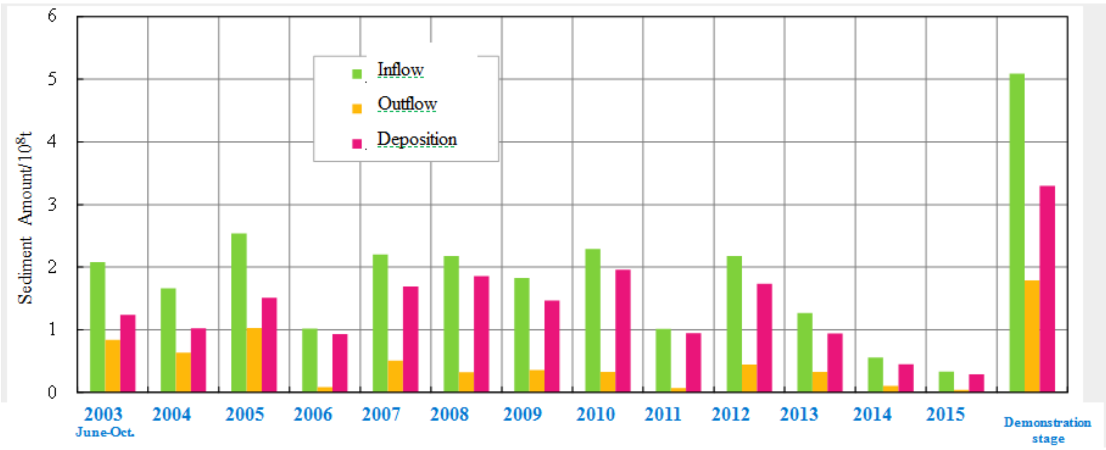


Fig.4.1-1 Annual sediment deposition amount in the Three Gorges Reservoir

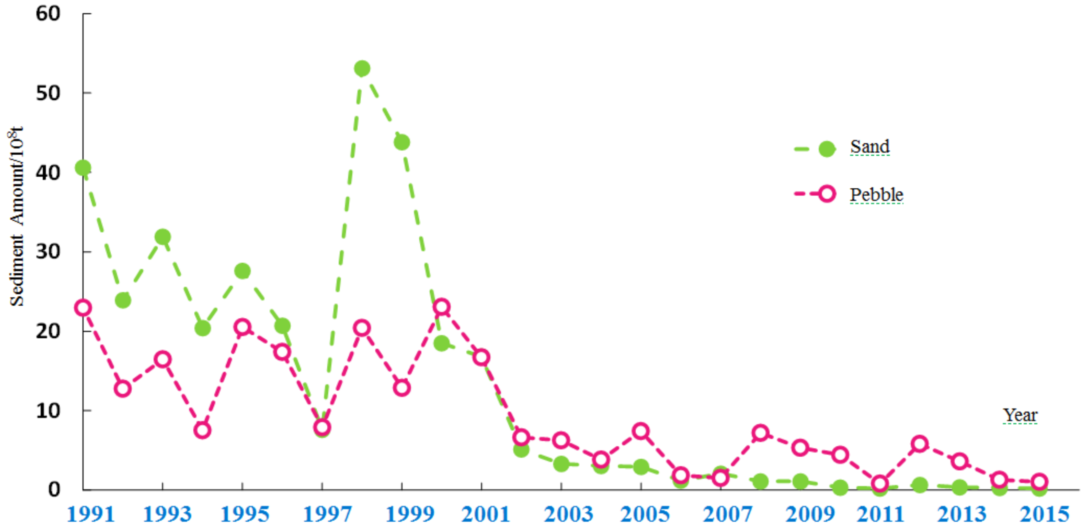


Fig.4.1-2 Bed load (Sand and pebble) transport amount at Cuntan Station

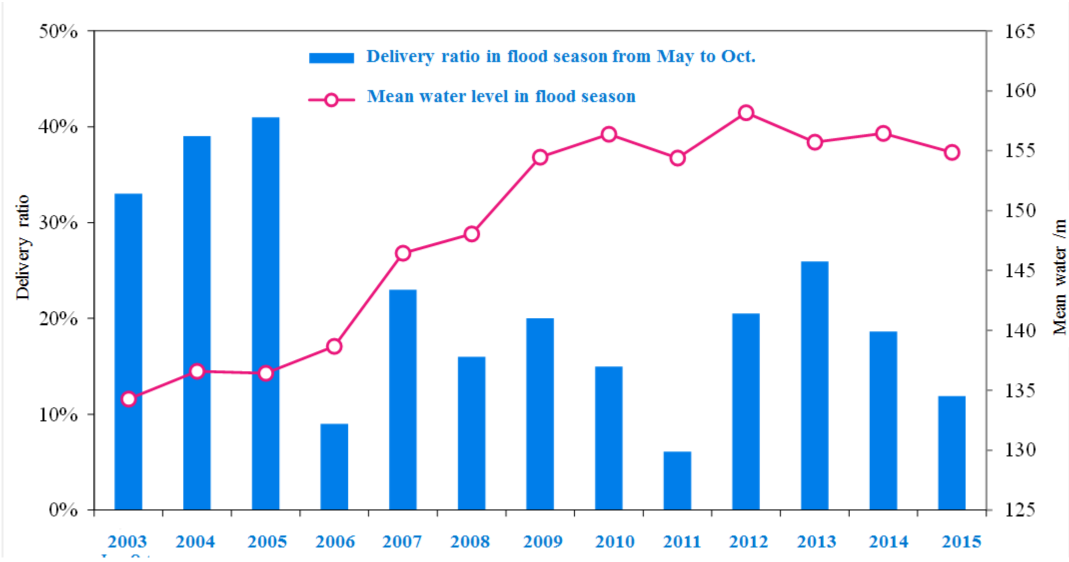


Fig.4.1-3 Variation of delivery ratio and mean water level of the Three Gorges Reservoir

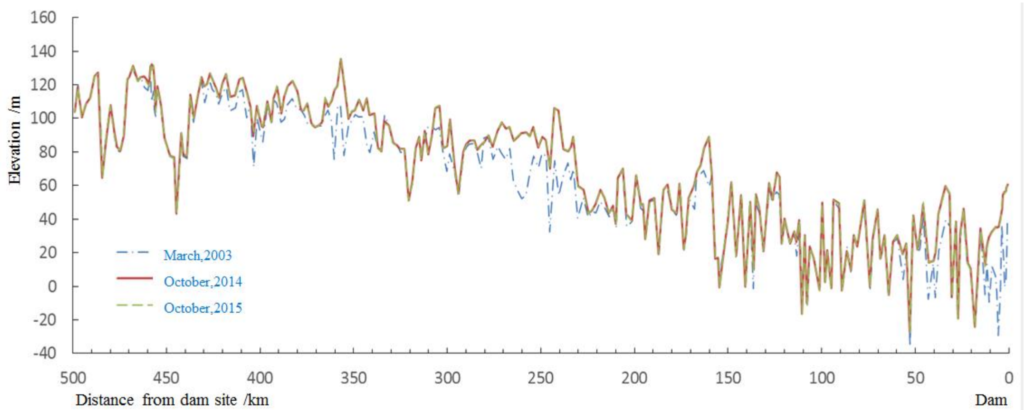


Fig.4.1-4 Change of bed longitudinal section in the Three Gorges Reservoir

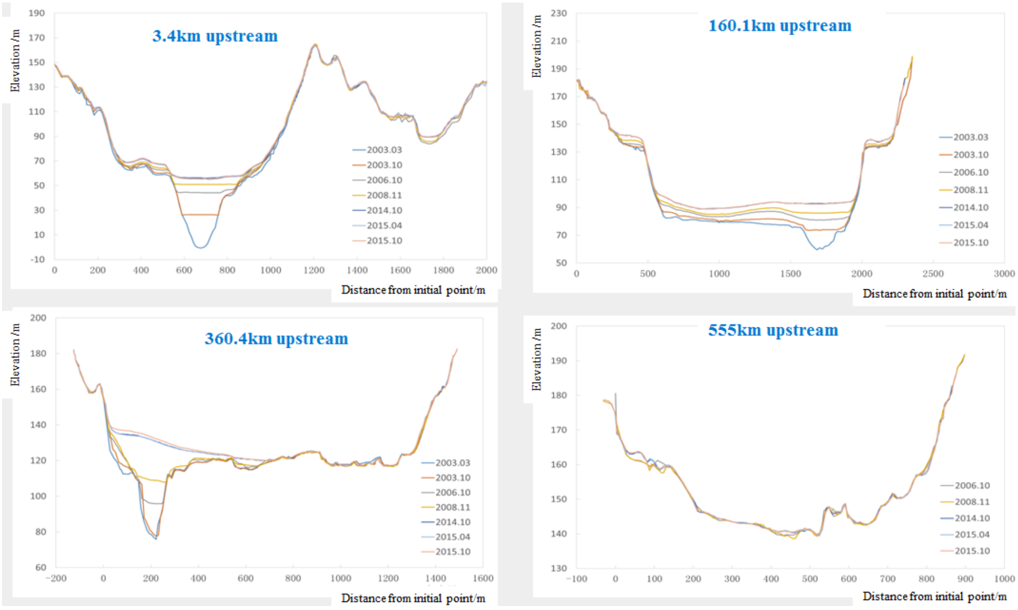


Fig.4.1-5 Variation of typical cross section reservoir of the Three Gorges Reservoir

4.2 Variation of flow and sediment along the downstream reach of TGP

The main stations along the downstream reach of TGP are marked on Figure 4.2-1. Similar to upstream, the runoff reduced slightly downstream after impoundment of TGP. But the sediment discharge reduced obviously after impoundment. The reduced ratio is becoming smaller and smaller from upstream to downstream. The water level decreased obviously in dry season along the downstream of TGP. The relationship between water level reduction at Shashi Station and erosion amount in upper Jingjiang reach at low channel is fit well. The elevation of the riverbed is obviously reduced. Erosion of main channel and low beach is the main change feature of cross-sections. See Figure 4.2-2 to Figure 4.2-7.

The results show that the concentrated scour in low-flow channels is related not just to the decrease in flood frequency and longer duration of medium flows, but to the characteristics of channel scour at a high rate under medium flows and a low rate under flood flows. At the Jianli station, the annual mean transport of coarse sediment (d > 0.125 mm) has recovered to the same multi-year mean level as before TGR impoundment, while most of the erosion in the long reach immediately downstream of Chenglingji was related to fine grain sediment. Channel erosion caused a significant drop in the medium and low river stages, and such a tendency showed a growing rate in the sandy reaches upstream from Chenglingji. However, the river stage did not drop considerably when the channel flow was above a certain threshold around the bankfull discharge.

Results show that the water level during low flowrate at Zhicheng station decreased slightly. Apart from that, the water level during medium and low flowrate decreased to some extent at stations in the upper Jingjiang reach, among which Shashi station witnessed the largest decline of low water level. The water level in lower Jingjiang reach also decreased slightly under the same flowrate. Moreover, the change of stage-discharge relation in Jingjiang reach is mainly caused by the Jingjiang river erosion, in particular, the erosion in the low water river channel.

On the basis of analyzing the sedimentation regularity since the operation of Three Gorges Reservoir, we made a comparison between the measured sedimentation(in terms of amount, distribution and sediment delivery ratio) and the sedimentation predicted by models developed by

Yangtze River Scientific Research Institute during the initial design, technical design, and follow-up planning stage. Results reveal that the predicted regularity of sedimentation is consistent with the measured value. When the incoming flow and sediment conditions and reservoir operation modes in the prediction are different from the actual conditions, the predicted sediment amount and delivery ratio are larger than the measured values; while when the prediction conditions are approximate to the actual conditions, the predicted values are close to measured values, which indicates that the prediction models and results are reliable. To increase the prediction accuracy, the mechanism of sediment transport should be further revealed, and the prediction models should be improved and checked based on measured data accumulation.

Due to sediment retention effects of reservoirs group in upper Yangtze River and reduction of sediment entering the Three Gorges Reservoir after operation of Three Gorges Project , significant decay of sediment discharge and severe river channel erosion are developing at the downstream of the Three Gorges Project, reaching a accumulative 1.6 billion m^3 erosion quantity from 2002 to 2015. At the same time, the bankfull river geometry also changed.

Fig.4.2-1 Distribution of the main stations along the downstream reach of TGP

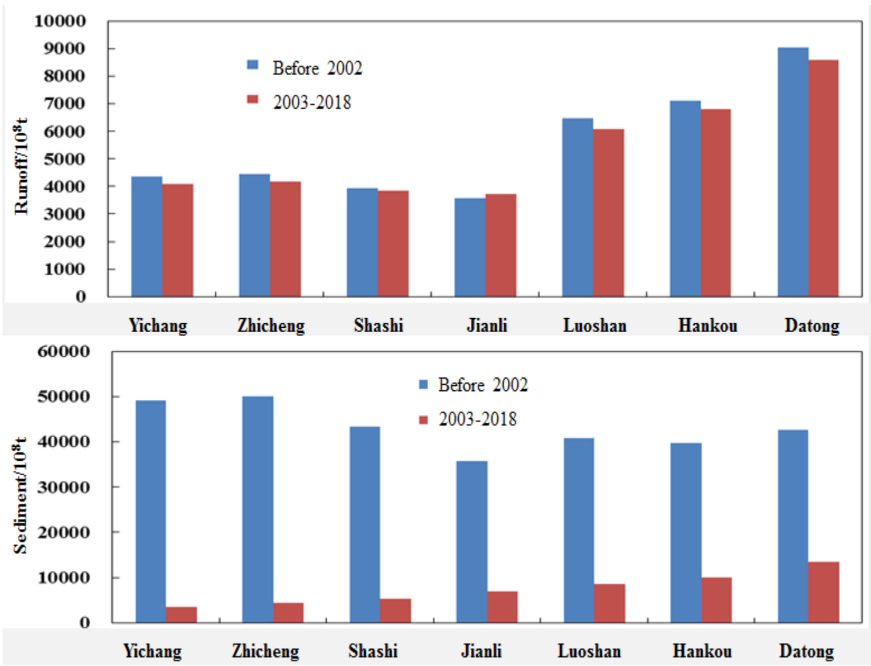


Fig.4.2-2 Variation of runoff and sediment along the downstream reach of TGP (1)

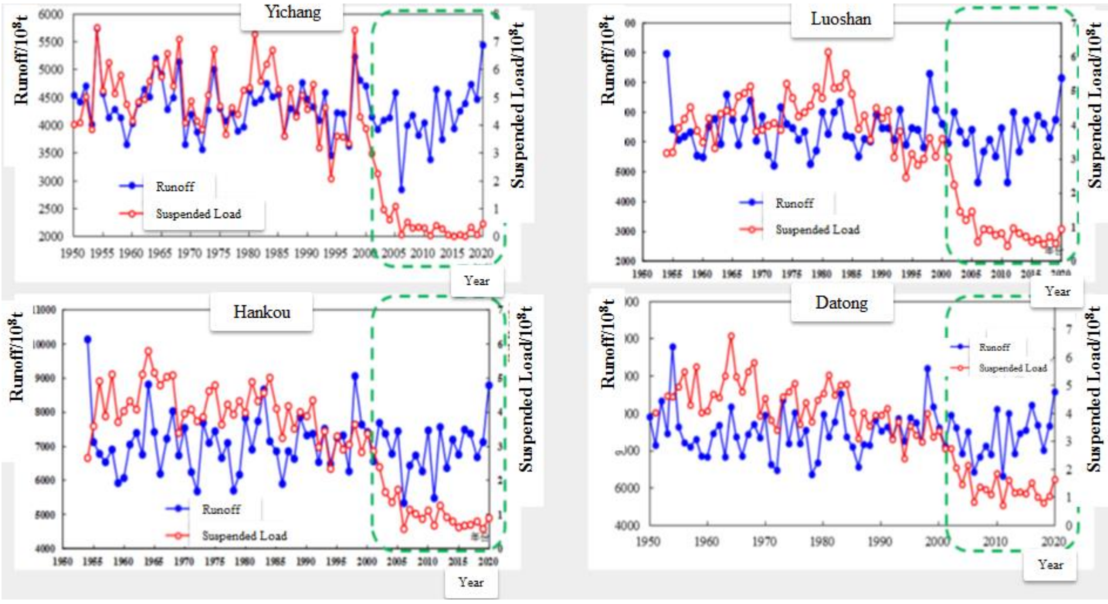


Fig.4.2-3 Variation of runoff and sediment along the downstream reach of TGP (2)

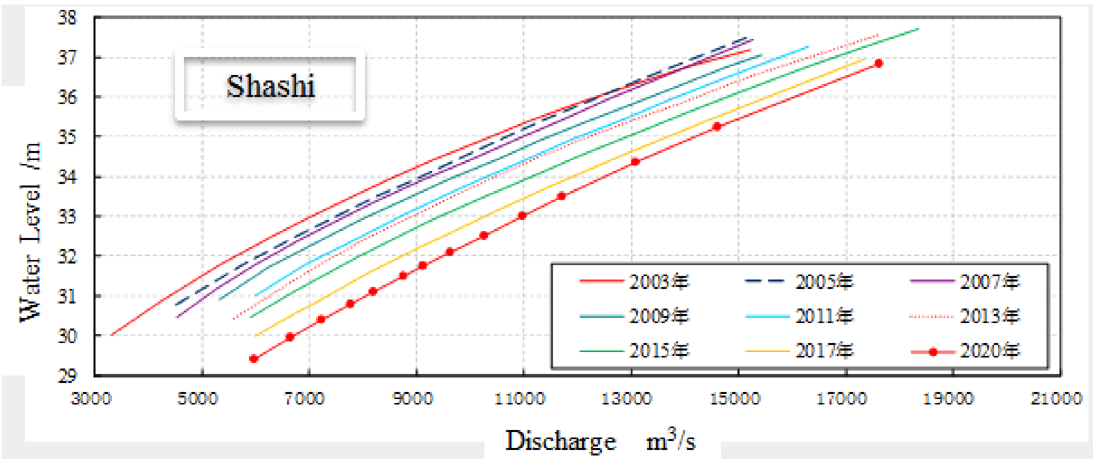


Fig.4.2-4 Change of rating curve at Shashi Station after impoundment of TGP

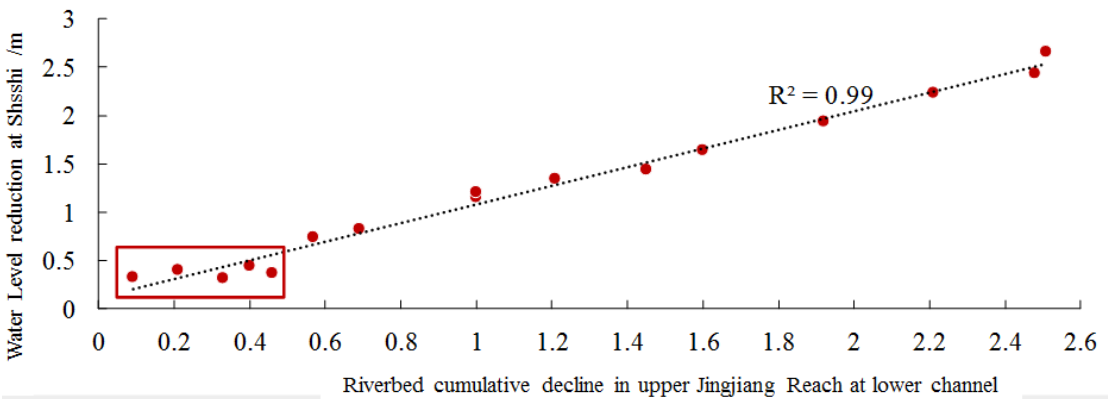


Fig.4.2-5 Relationship between water level reduction at Shashi Station and erosion amount in low channel

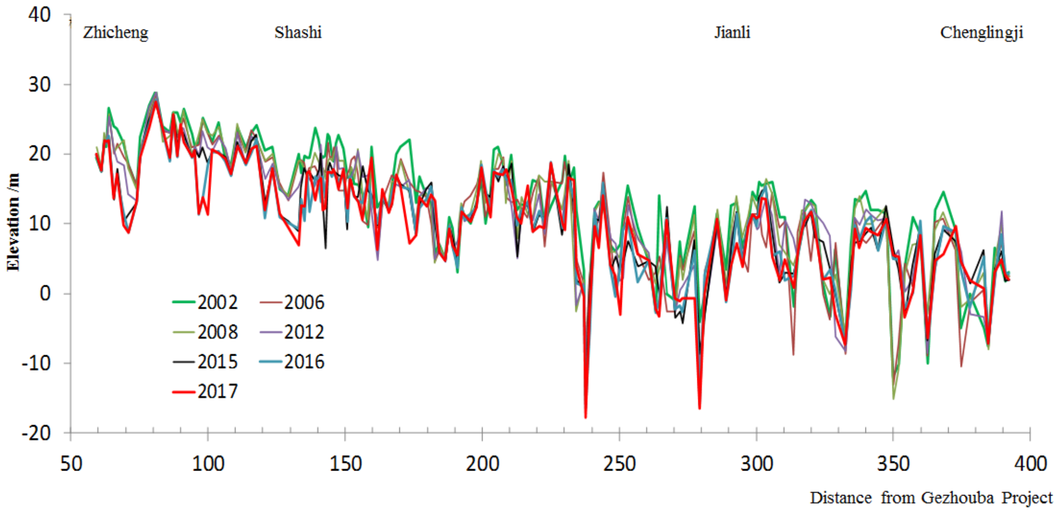


Fig.4.2-6 Change of bed longitudinal section in the downstream reach of TGP

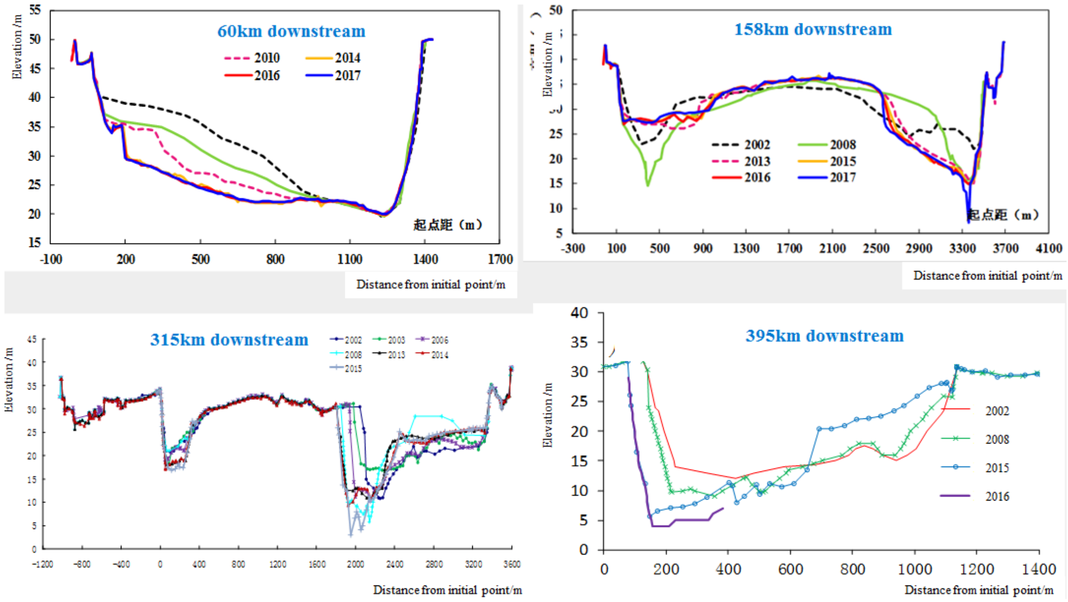


Fig.4.2-7 Change of cross-sections in the downstream reach of TGP

4.3 Typical bank collapse along the downstream reach of TGP

Bank collapse is one of the evolution characteristics of alluvial rivers in natural condition. Bank failure plays a vital role in fluvial processes and river pattern transformation in meandering rivers, driving lateral migration and increasing channel sinuosity. Before the Three Gorges Project was impounded, bank collapse occurred occasionally. After operation of TGP, the flow and sediment conditions in the Jingjiang River changed greatly, causing frequent bank collapse in recent years and influencing the stability of the local river regime and the safety of river channel flood control.

See Figure 4.3-1. The government invested money in bank revetment to make the embankment safe.

By using BSTEM (Bank Stability and Toe Erosion Model, see Figure 4.3-2), the stability safety factors of many typical sections are calculated respectively under different conditions. These conditions include bank slope morphology, water level, lateral erosion distance of toe, vegetation type and revetment project. The impact of the factors on the river bank slope stability is also analyzed. Results show that water level variation has significant impact on riverbank stability. The stability of bank slope with high and low water levels is closely related with the riverbank composition. When the rate of water level recession is high, the safety factor reduces remarkably which is prone to cause bank collapse. It also shows that the safety factors are different in different bank slope morphologies, and the safety factor decreases as the lateral erosion distance of toe increases. Revetment project and vegetation coverage will increase the bank slope stability.

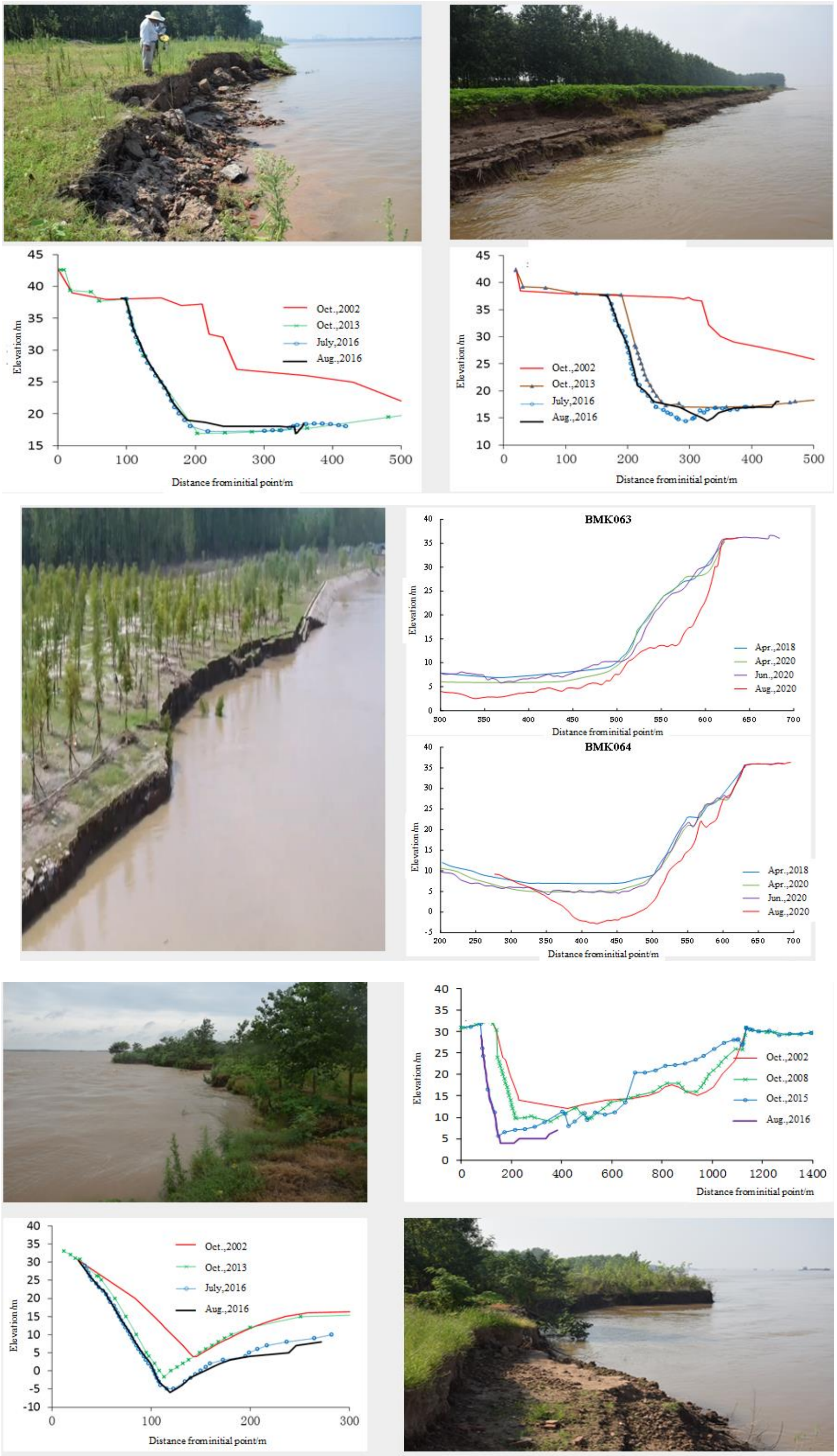


Fig.4.3-1 Picture of typical bank collapse and change of bank slope in downstream reach of TGP

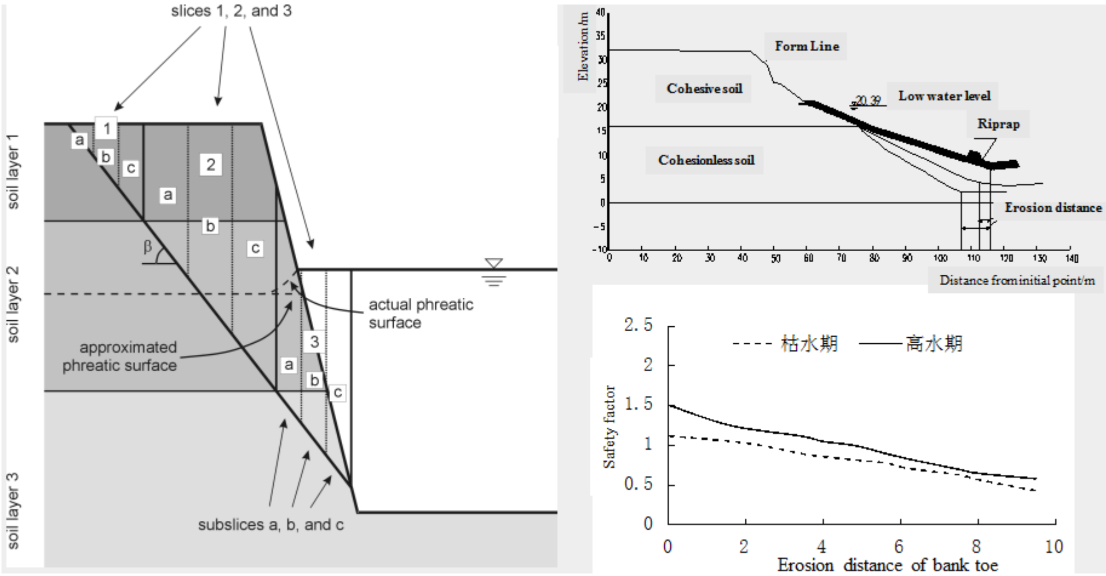


Fig.4.3-2 Schematic diagram of BSTEM Model

Over the years, a large number of bank protection projects have been built along the middle and lower reaches of the Yangtze River. The main revetment types are smooth type, wire mesh, facing brick of low water platform, mold pebble row, concrete hinge row, wire basket of pebble, mould package concrete, and so on. See Figure 4.3-3 to Figure 4.3-4.

Fig.4.3-3 Typical bank revetment in middle and lower reach of the Yangtze River (1)

Fig.4.3-4 Typical bank revetment in middle and lower reach of the Yangtze River (2)

REFERENCES

JIANG Jianping， ZHU Hanhua， WU Lijian. Study on rapid measurement method for sediment concentration based on laser scattering[J].Yangtze River,2020,51(7):89-92

JIN Zhong-wu, REN Shi, WU Hua-li, ZHU Shuai, WANG Yu-xuan, LI Qiu-li. Sedimentation and Sediment Delivery and River Pattern Conversion in the Three Gorges Reservoir[J]. JOURNAL OF YANGTZE RIVER SCIENTIFIC RESEARCH INSTI, 2020, 37(10): 9-15.

CHEN GUI-ya, YUAN Jing, XU Quan-xi. On sediment diversion ratio after the impoundment of the Three Gorges Project [J] , Yangtze River,2012, 23(3): 355-362.

LI Wenjie, LI Na, YANG Shengfa, WANG Tao. Analysis of the sedimentation in the Three Gorges Reservoir based on the sediment carrying capacity. Advances in Water Science, 2016, 27(5): 726-734.

GUO Xiao-hu, QU Geng, ZHU Yong-hui. Changes of the Stage Discharge Relation in Jingjiang River after the Impoundment of Three Gorges Reservoir [J]. JOURNAL OF YANGTZE RIVER SCIENTIFIC RESEARCH INSTI, 2011, 28(7): 82-86.

LU Jin-you, HUANG Yue. Comparison of Sedimentation in Three Gorges Reservoir between Calculated Prediction and Prototype Measurement[J]. JOURNAL OF YANGTZE RIVER SCIENTIFIC RESEARCH INSTI, 2013, 30(12): 1-6.

XIA Junqiang, LIN Fenfen, ZHOU Meirong, DENG Shanshan, PENG Yuming. Bank retreat processes and characteristics in the Jingjiang Reach after the Three Gorges Project operation. Advances in Water Science, 2017, 28(4): 543-552.

GUO Yi, SUN Zhaohua, LUO Fangbing. Time-variation characteristics and causes of Yichang low-water level since impoundment of Three Gorges reservoir[J]. Hydro-Science and Engineering, 2017, (4): 35-42.

WANG Bo, YAO Shi-ming, YUE Hong-yan. Stability Analysis for Typical Riverbank Slope in the Middle Reach of Yangtze River by BSTEM[J]. JOURNAL OF YANGTZE RIVER SCIENTIFIC RESEARCH INSTI, 2014, 31(1): 1-7.