SEDIMENT MONITORING AND MODELING PRACTICE OF THREE GORGES PROJECT IN CHANGJIANG RIVER

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Abstract:
Three Gorges Project (TGP) is a key project for the exploitation and governing of Changjiang River (Yangtze River), which has large benefit of flood control, power generation and navigation. After the TGP was put into operation, the movement process of flow and sediment will be changed, on one hand, with the rise up of the water level before dam, for the decreasing of velocity and sediment-carrying capacity, large amount of sediment will be deposited in reservoir, on the other hand, with the decreasing of sediment concentration in the downstream of reservoir, serious scouring with long time and distance on the riverbed in the downstream is appeared. Therefore, the sediment deposition and scouring is one of the key technical issues in the construction of TGP, and high attention has been given to it by the china government.
From 1993, when the TGP is brought into construction, the Bureau of Hydrology (BOH), Changjiang Water Resources Commission (CWRC) , has developed large scale and continues prototype observation scheme for sediment monitoring in Changjiang River. The measured data indicates that during the 5 years of the construction of TGP, the incoming suspended load is 0.9505 billion tons and if the incoming sediment from the three gorges interval is not considered, the silted suspended load in the area of Three Gorges Reservoir is 0.6397 billon tons, and the sediment evacuation is 32.7％. From Yichang to Hukou which is one reach in the downstream of TGP, the scoured sediment volume is 0.689 billion m^3， which is centered in the reach of Yichang to Chenglingji mainly.
At the same time, using the large amount of flow and sediment observations, in BOH_CWRC, a 1-dimentional (1D) and a 2-dimentional (2D) flow and sediment models are developed for Changjiang River and the silting process in the reservoir region and scour process downstream of the three gorges dam is simulated, which offered abundance data base and the most reliable accordance for sediment management in reservoir.
Keywords: Changjiang River, Three Gorges Reservoir, sediment, prototype observation, flow and sediment modeling

1 Introduction

TGP is the largest multi-purpose development water conservancy project ever built in China, and it is a key backbone project for the flood control, navigation and water resources development of Changjiang River. It is 40km upstream of the Gezhouba Dam, situated at Three Gorges section of upper reaches of Changjiang River, which controls a drainage area of 1 million km^2. The Three Gorges Reservoir(TGR) is designed to have a normal pool level of 175m above sea level with a corresponding aggregated storage capacity of 39.3 billion m^3, and a flood control level of 145m with a flood control capacity of 22.15 billion m^3. The length of the TGR is over 600km and its average width is about 1.1km. It will be of great significance to the flood control efforts in the middle reach of Changjiang River. The total installed capacity of TGP will be 18.2 GW and the average annual output will be 84.7billion KWh. The navigation conditions will be improved in the entire 600km long channel in the reservoir area.

Sediment problem is one of the key technical issues of TGP. After the TGP was put into operation, large amounts of sediment will be deposited in reservoir and serious scouring will be happened to the riverbed at the downstream of reservoir. Therefore, sediment problem is one of the key technical issues during the construction and operation of TGP. To this problem, high attention has been paid by government on the sediment issues, and in Changjiang River, also, in BOH_CWRC, a lot of human, physical and financial resources have been devoted into prototype observation on the sediment in TGP. During the observation, abundant information has been collected including water level, discharge, suspended load, bed-load sediment, scouring and deposition to riverbed, and river channel processing of the key reaches, which offered abundant data to the research of scouring and deposition character in Changjiang River or the further study of flow and sediment modeling, which facilitate the development of sediment subject in Changjiang River. On the other hand, after the TGP was put into operation, through systemic analysis to the flow and sediment process or the scouring and deposition to the riverbed of Changjiang River with numerical modeling, technical supporting is provided to the prototype observation arrangement of hydrology and river channel morphology, and it has quite important significance for mastering the rule of riverbed evolution, or the flow and sediment transportation.

Flow and sediment modeling is one in common used method for the riverbed deformation forecasting in reservoirs and rivers. Until now, the models of China Institute of Water Resources and Hydropower Research (IWHR), Changjiang River Scientific Research Institute(CRSRI) and Tsinghua University based on 1-D imbalance sediment transport theory is applied broadly, however, due to the complex nature of the problem and considering the present status of sediment studies, results of the research work were regarded as preliminary and qualitative. Furthermore, after the TGP was put into operation, large changes have been happened to the flow and sediment process, riverbed boundaries and etc. Whether the experienced parameter or disposal in the available modeling can adapt the future development of TGP or not, further study with the new prototype data is needed.

In this paper, firstly, the sediment monitoring about TGP in Changjiang river is introduced, then some research results about the sediment in TGR and downstream of it is depicted and compared with the measured data. Finally, based on the theory of sediment movement, and with abundant hydrologic and riverbed prototype observation data, the long-reach flow and sediment modeling is developed to simulate the deposition process in the reservoir region and scouring process downstream of the dam. During the simulation of deposition process in the reservoir region, the model is verified with the measured data after the impoundment of TGP, and then, the parameters fit with the movement character of flow and sediment in reservoir region is acquired. Secondly, the 2D model is mainly used to simulate the process of sediment transportation in local reaches, whose mainstream sways in a large range, and river regime is always change, or the scouring and deposition degree is very large. In this paper, considering that different river regime and scouring or deposition character exists in different kinds of reaches, so, the Tunaozi, Shashi and Wuhan reach are regarded as the example separately, and the 2D model is mainly used to simulate the process of sediment transportation in Tunaozi reach during the degrading stage of reservoir. Using these models, the scouring and deposition process is simulated in the meandering river reach near Shashi city and the braided river reach near Wuhan city at the middle stream of Changjiang River

2 Sediment Prototype Observation

The sediment issue of TGP is an important technology problem. Sediment prototype observation is the unique base of physical model test, numerical simulation, and theoretical analysis, and it plays a very important role in the determination of construction schedule, regulation operation, sediment research condition.

The sediment observation based on the TGP definition, design and construction, are all unprecedented in terms of deepness, extent and scale, and the accomplished observation and analysis result is abundant also, and rules of the characteristics of the runoff and sediment transport in the upper reaches of Changjiang River, the reservoir sedimentation especially in variable backwater area and scouring in downstream channel, are appeared preliminarily. Scientific reference is provided by the TGP sediment prototype observation for the TGP's definition and planning and design, and decision-making reference is also provided for the construction security.

Observed data are crucial to the safe operation of TGP and are the most reliable information for verifying previous predictions or for improving research methods applied in research work on sediment problem of TGP.

2.1 Observation goal

The observation in definition phase is executed to serve the sediment research, and the observation in construction phase is executed to serve construction and operation of TGP. After the reservoir began its storage and the water level before dam reached 135m 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 and make scientific reference for the reservoir's regulation optimization, increase of benefits contribution of TGP, and decrease of negative influence. The observation goal includes the following aspects:

(1) Mastering the background data of natural channel status both in upper and lower reaches before impounding completely;

(2) Making reference for the decision of installment impounding plan;

(3) Real time monitoring of the variation of scour and deposition both in upper and lower reaches after impounding, and finding out the problems, so as to take countermeasure in time;

(4) Validating the simulation technology adopted (including main parameter), and increasing the credibility of TGP sediment forecasting.

The above aspects will be kept being observed and analyzed and researched after 2009, so as to make reference for the optimization of reservoir's deployment.

2.2 Observation region

Sediment prototype observation of TGP is caught great attention of China government. The sediment prototype observation should be permeated in every phase including definition phase (before 1993), design and construction phase (1993-2009), and storage and operation phase (after 2010). The observation in definition phase, including analogical observation, aims at sediment research, and observation in design and construction phase.

Field observations of TGP covers three regions: the complete reservoir region, the dam section (i.e., partial reservoir area close to the dam plus the river channel between the Three Gorges Dam and Gezhouba Dam), and locations of major hydrometric stations on the downstream river section between Yichang and Hukou. Areas to be observed change constantly as required in different periods of the construction of TGP with various pool levels. In the cofferdam impoundment period from 2003 to 2006, the observation region includes the followings:

(1) The reservoir region: including a reach from the dam to Lidu Town on the mainstream of Changjiang River, 494km (approx.) in length, and several tributary reaches with a total length of 210km (approx.) in 10 tributaries, and Qingxichang station was used as the reservoir inflow control station during this period, which is 473.8km from the Three Gorges Dam;

(2) The dam region: this reach has a total length of 57km. The first 31km starts from Miaohe upstream of the TGP and ends at Liantuo downstream of the TGP. The remaining 26km is also called "the section between two Dams", which starts from Liantuo and ends at the Gezhouba Dam; Huanglingmiao station is used as the reservoir outflow control station;

(3) The downstream region: this area from Yichang to Hukou covers the entire middle reaches and part of the lower reaches of the Changjiang River, with a total length of 1010km. It includes the Dongting Lake with an area of 2700km^2, i.e., the East, South and West Lake areas. It also includes diversion channels from the Changjiang River to the Dongting Lake, with a total length of 914km, i.e., the Songzi, Hudu and Ouchi River channels.

Data collected in these areas include water level, flow velocity and direction, discharge, sediment load and particle size distribution, topography, regular stream cross-section measurement, and fluvial processes at key reaches.

From 1993 till August 2006, hydrological and sediment transport data were collected for a total of 542 station-years, streambed were mapped for a total area of 12573km^2, sediment samples were taken and analyzed for a total of 25650 vertical-times, and measurements of regular streambed cross-sections were performed as many as 8519 cross-section-times.

All the observations were conducted in accordance with the national and industrial technical standard, with strict quality control measures applied according to the ISO9001 Quality Management System. Accuracy of observed data has been greatly improved thanks to the application of new methods and technologies, such as kinematic GPS (RTK) survey, electronic plane-table surveying system, Acoustics Doppler Current Profiler (ADCP), network technology, dual-frequency digital echo sounder, multi-beam bathymeter mapping equipment, etc. A Hydrologic and Sediment Transport Database of TGP has been developed independently by the Three Gorges Hydrology and Water Resources Bureau, which can manage the collected data in a unified, scientific and efficient manner.

2.3 Summary of the Sediment Monitoring

2.3.1 Sediment Deposition in Reservoir Area

2.3.1.1 Sediment Deposition volume

The runoff of Changjiang River comes mainly from the Jinsha, Minjiang, Tuojiang, Jialing and Wujiang rivers, while the suspended load comes mainly from the Jinsha River and Jialing River.

According to the statistics and analysis of the main control stations of TGR, such as the station names Cuntan, Wulong and Huanglingmiao, from June.2003 to December.2007, the incoming suspended load is 0.9505 billion tons and if the incoming sediment from the three gorges interval is not considered, the silted suspended load in the area of Three Gorges Reservoir is 0.6397 billon tons.

To describe respectively, from June.2003 to December.2006, the incoming suspended load is 0.73 billion tons, the outlet suspended load from TGR is 0.26 billon tons, and if the incoming sediment from the three gorges interval is not considered, the silted suspended load in the area of TGR is 0.47 billon tons. In 2007, the incoming suspended load is 0.22 billion tons, the outlet suspended load from TGR is 0.051 billon tons, and if the incoming sediment from the three gorges interval is not considered, the silted suspended load in the area of TGR is 0.169 billon tons.

2.3.1.2 Sediment evacuation proportion

According to the analysis of the prototype data, it is educed that the sediment evacuation is 32.7% from 2003 to 2007. In which, from June.2003 to December.2006, the sediment evacuation is 35.6 %.

In 2007, the sediment evacuation is 23.1%, and the sediment evacuation in flood season is 26%, the largest sediment evacuation in August is 44%. In the falling period, the water level before dam falls from 147.5m (May.15) to 144.6m (May.31), the average inflow discharge is 7680m^3/s, the amount of deposition in reservoir area is 4400 thousand tons, and the sediment evacuation is 1.5%. During the period of impoundment of 156m, from Sep.23 to Oct.25, the average inflow discharge is 14600m^3/s, the incoming suspended load is 0.015 billion tons, the outlet suspended load from TGR is 1770 thousand tons, the silted suspended load in the area of TGR is 0.0137 billon tons, and the sediment evacuation is 11.5%.

To sum up, the incoming suspended load of TGR is mainly centered in flood season, and the sediment evacuation has a close relationship with many conditions, such as inflow and sediment, water level before dam, the deployment scheme, and etc.

2.3.1.3 Sediment deposition shape and distribution

According to the measured topography of TGR region from Mar.2003 to Sep. 2007, a large proportion of sediment depositions, which accounts for 94% of the total amount and was accumulated in the broad-valley sections of reservoir, while little deposition or even slight scouring was found in the narrow valley of reservoir region.

To see the distribution of sedimentation along the reach, it can be educed that the nearer to the dam, the larger intensity of deposition happens, and from the dam to Miaohe, the total deposition is 0.071 billion m^3, and 81% of the sediment was deposited below the elevation of 90m and the particle size was fine, therefore it has no effect on the operation of TGP.

2.3.2 Degradation downstream of the TGR

The river channel downstream of the TGR from Yichang to Hukou, about 954km long, belongs to the middle reaches of Changjiang River, and it is an alluvial stream with fine bed materials. Although under the natural conditions, deposition and scour of the river channel took place frequently and, the river reach from Yichang to Hukou was basically in a state of dynamic quasi-equilibrium in the several decades before the construction of TGP.

Since the impoundment of TGR, the above-mentioned situation has been changed. A comparison between channel topographies of pre-dam and post-dam periods was made. From Oct.2002 to Oct.2007, the total scouring amount in reach between Yichang and Hukou is 0.689 billion m^3, while channel scouring focused in the average bed, which accounts for 85% of the total amount, and the average degradation intensity is 720,000m^3/km.

To see the degradation volume along the time, from Oct.2002 to Oct.2003, the sediment degradation volume from Yichang to Hukou is 0.193 billion m^3, which accounts for 28% of the total volume. From Oct.2003 to Oct.2007, sediment degradation volume to the riverbed from Yichang to Hukou is 0.496 billion m^3, which accounts for 72% of the total volume, in which the most serious degradation happens from Oct.2004 to Oct.2005, and the sediment degradation volume to the riverbed from Yichang to Hukou is 0.295 billion m^3, which accounts for 43% of the total volume.

3 Preliminary examination of the previous research

3.1 Variations of Runoff and Sediment Load Downstream of the TGP

Observed annual runoff and sediment load at the stations from 2003 to 2006 are compared with long-term average values (1950~2002) in Table 3. It can be seen that the annual runoff at various stations generally remain the same as their long-term average, but the annual sediment loads were reduced significantly due to the combined effects of sediment trapping by the TGP, reduction of sediment transport from upstream catchments and sand-gravel mining from streambed, such as the annual runoff of Yichang, Hankou and Datong have changed little, but the annual sediment has decreased obviously by 86%, 67% and 62% respectively, and the annual sediment discharge at Yichang, Hankou and Datong station is 0.702×10^8t, 1.34×10^8t and 1.63×10^8t separately. Reduction in sediment load became smaller for stations further away from the dam, i.e., sediment concentration recovers progressively downstream which suggests that channel scour occurred.

Table 3 Variation of annual sediment load at major hydrometric stations downstream of the TGP as compared with long-term average values

Control station		Yichang	Shashi	Jianli	Luoshan	Datong
Runoff ($\times10^9m^3$)	1950～2002	436.9	394.2	357.6	646.0	905.2
	1991～2006	392.0	370.8	353.8	585.7	825.8
	Variation	-10%	-6%	-1%	-9%	-9%
Sediment load ($\times10^6$ tons)	1950～2002	492.0	434.0	358.0	409.0	427.0
	1991～2006	70.2	97.5	104.0	119.0	163.0
	Variation	-85%	-77%	-70%	-70%	-61%
Sediment concentration (kg/m^3)	1950～2002	1.13	1.10	1.00	0.633	0.472
	1991～2006	0.179	0.263	0.294	0.203	0.197
	Variation	-84%	-76%	-71%	-68%	-58%

3.2 Computation for reservoir sedimentation

The deployment rule of TGP is "impounding the clear in the non-flood season and releasing the muddy in the flood season". The released discharge from reservoir was calculated by reservoir routing. Two 1-D sediment mathematical models, developed by the Changjiang River Water Resources Institute and China Institute of Water Resources and Hydropower Research respectively, were used to calculate reservoir sedimentation. The two models are based on the theory of non-equilibrium transport of sediment load and have been verified by the field data of Changjiang River and Hanjiang River (Danjiangkou Hydro-project). Fig. 1 shows one part of the calculated results.

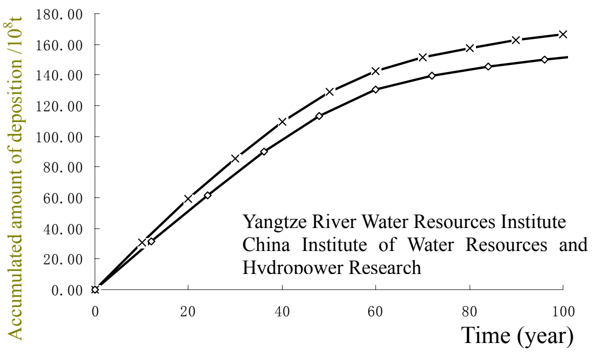

Fig. 1 Accumulative deposition amount in Three Gorges Reservoir

The research in the past was focused on variation of mean values, while only 4-year field data are available at present. Therefore, it is difficult to make direct comparison at this time. The hydrological series in calculation were from 1961 to 1970 and used repeatedly. The mean annual values of this series were representative, but the sequence of wet and dry years were not representative. As a preliminary comparison, only mean values can be used to make comparison, but not a year-to-year comparison. Strictly speaking, the mean value of a certain years is not equal to the mean value in a different period of years. Consequently, such a comparison is rough and tentative.

The comparison of the calculated results and field data is shown in Fig.2. The first 10-year mean annual incoming sediment load into the Three Gorges Reservoir (Cuntan and Wulong Stations) was adopted as 0.509 billion tons in the feasibility study. According to the calculated results of mathematical models, the first 10-year released mean annual sediment load from the reservoir was 0.154 billion tons and 0.355 billion tons of sediment deposited in the reservoir and the trap efficiency was 70%. From 2003 to 2006, the mean annual incoming sediment load (Cuntan and Wulong station) was 0.198 billion tons, the mean annual released sediment load (Huanglingmiao Station) was 0.07 billion tons and 0.128 billion tons of sediment deposited in the reservoir with a trap efficiency of 65%. The amount of deposits in the reservoir in three years was only 36% of the predicted. The reason was that the incoming annual sediment load was much less, only 39% of the designed value. When the actual annual runoffs and sediment loads in 2003 and 2004 were used in the calculation by the same sediment mathematical model, the calculated results are almost the same as the actual values (Fig.2). Slow development of deposition with small amount of deposition in the reservoir is favorable for maintaining the effective storage capacity of reservoir and management of navigable channels.

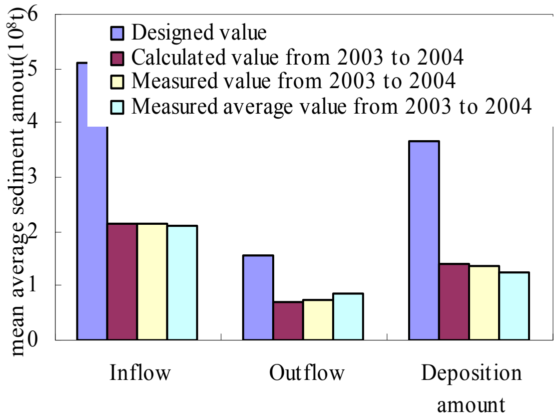

Fig.2 Comparison of Measured and Calculated annual amount of deposition in Three Gorges Reservoir

The longitudinal distribution of deposition in the reservoir was also different from that of the calculated. Based on the measured cross-sections, the nearer to the dam, the intensity of the deposition is larger. However, the calculated results in the first 10 years showed less deposition near the dam. The deposition in the upstream approaching channel and the flow conditions near the intakes of power plant are closely related to the intensity of deposition in the reservoir area. Sediment measurement in front of the dam should be strengthened and the sediment mathematical models should be improved in the future.

3.3 Degradation downstream from the dam

During the design stage of TGP, the initial channel topography for sediment mathematical modeling of degradation in the reach from Yichang to Datong below the dam was the topography measured in October 1993. The incoming flow and sediment load were the released values from the reservoir calculated by mathematical model based on the hydrological series from 1961 to 1970. The calculated results of the accumulated degradation from Yichang to Datong and the first 10-year process from Yichang to Chenglingji are shown in Fig.3 and Fig.4 respectively.

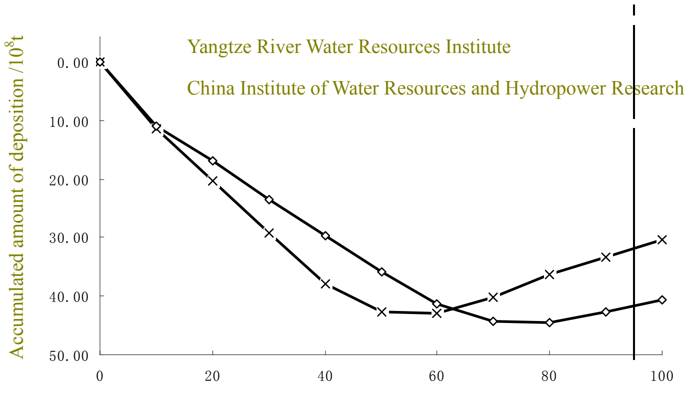

Fig. 3 Accumulative degradation amount from Yichang to Datong of Changjiang River

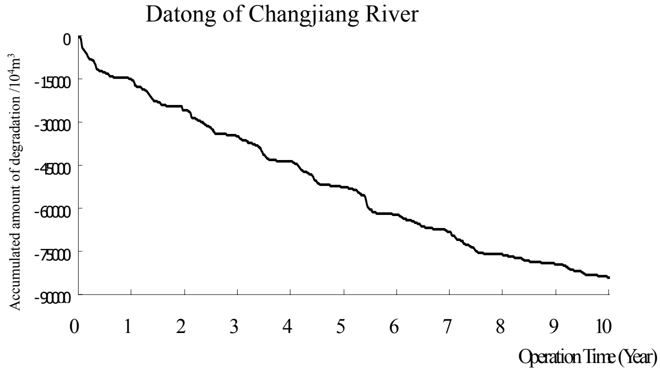

Fig.4 Accumulated degradation amount in the first 10 years from Yichang to Chenglingji of Changjiang River

Fig 5 shows the comparison between the calculated results of degradation in the first 10-year period after the TGP was set up and the field data (mean value from 2003 to 2006). The calculation was completed in the period from 1991 to 1995. The field data were based on the measured fixed cross-sections. The measured amount of degradation from Yichang to Jiujiang was 0.124 billion tons, which is larger than that of the calculated, i.e., 0.0875 billion tons. Either in the total river section (from Yichang to Jiujiang) or in the sub-sections, the actual amount of degradation was larger than that of the predicted, the distance away from dam is further, and the difference between the measured and calculated results is larger, and the development of degradation in the reach downstream of dam was faster than the predicted.

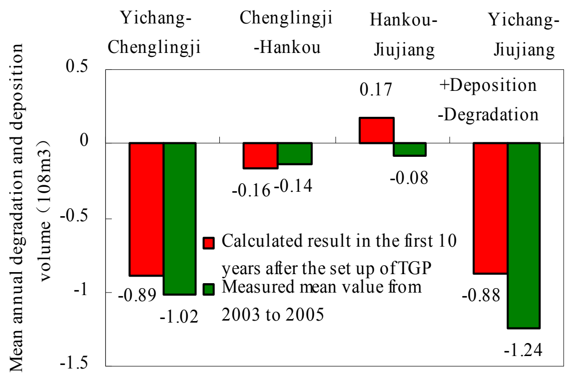

Fig. 5 Measured and calculated values of channel degradation below Three Gorges Project

After the impoundment of TGP, the erosion intensity is not only much larger than the pre-dam period, but also than the calculated result by numerical models. By analysis, there are three reasons: firstly, since 1990, the sediment load in upper Changjiang River has reduced obviously. At Cuntan station of Changjiang River, from 1991 to 2003, the mean annual sediment discharge reduces 29% compared with the years before 1990. At Yichang station, from 1991 to 2003, the mean annual sediment discharge is about 0.391 billion tons, which has reduced 25％comparing with the years from 1950 to 1990. From 2003 to 2006, the incoming sediment to TGP has reduced to 50% less than the mean annual value in the pre-dam period. Secondly, the trap efficiency of TGP is high, which is larger than 64%. It induce the sediment load entered the reach below dam reduced further, which results in sediment-starvation of flow and increasing the erosion intensity of riverbed. Thirdly, the activities of sand-gravel extraction have impact on sediment discharge. According to survey and statistic in 2005, from 2003 to 2005, the total quality of sand-gravel extraction between Yichang and Shashi reach is about 0.021～0.038 billion tons. The mean annual quality is about 0.007～0.013 billion tons, which is about 6％～12％ from Yichang and Chenglingji reach. So, the real conclusion should be based on long-term field data, and the improvement of field measurement technology and sediment mathematical models are also needed.

4 1D Flow and Sediment Modeling in Changjiang River

1-D flow and sediment modeling is mostly used to study the scouring and deposition process in long reach of long time. After the reservoir is built up, on one side, for the rising up of water level, the flow velocity and sediment carrying ability is decreased, and a great deal of sediment is silted up in the reservoir region. On the other hand, “the clean water let out” will decrease the sediment concentration of downstream, which will cause the long time and long scale scouring at the downstream. After the construction of TGP, to some degree, the sediment volume silted in the reservoir region is less than the designed value, at the same time, in the downstream of TGP, the sediment volume scoured at the downstream is larger than expected.

So, to study the scouring and deposition character in the reservoir region and the downstream of dam after the construction of TGP, in this paper, the 1-D flow and sediment modeling is applied, and the two reaches, one is from Qingxichang to dam, the other is from Yichang to Chenglingji are regarded as the example, the 1-D modeling of reservoir and downstream of the dam is set up, based on the prototype monitoring data, the model is calibrated and the calculated precision is verified.

4.1 1D Flow and Sediment Modeling in Three Gorges Reservoir Region

4.1.1 Before 135m Impoundment

To analyze the flow and sediment movement character in reservoir region before the impoundment of 135m, and considering the section data in reservoir region from Qingxichang to dam is available in Oct.2000 and 2001, in this paper, to verifying the model’s calculating precision, the flow and sediment process from Oct.2000 to 2001 is applied as the calculation condition of the model. The inlet of the calculating region is Qingxichang, and the Taipingxi is confirmed as the outlet.

The calculated conclusion indicates that the model can simulate the scouring and deposition process in the reservoir region, and the calculated process of discharge, sediment concentration, water level gradation and scouring process tallies well with the measured value.(see fig.1), and the error is controlled within the permitted range. At the same time, according to the measured topography between Oct.2000 and 2001, as a whole, it is scoured from Qingxichang to Taipingxi, comparing with the measured volume of 9.04 million m^3, the error of calculated value is 22%. The above result indicates that the model can be applied into the flow and sediment calculation before the impoundment of reservoir, and the calculating precision is very high.

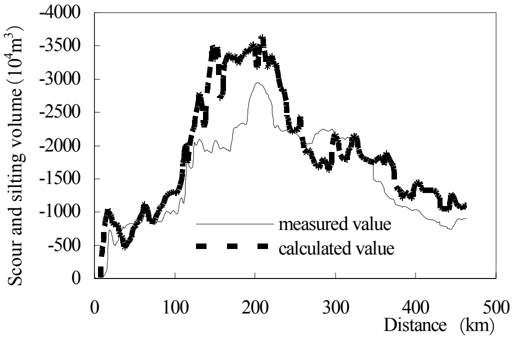

Fig.1 Comparison between calculated and measured value of accumulated scouring and deposition volume along the reach from Oct.2000 to 2001 in reservoir region ("—"delegates scouring, and "+"delegates deposition)

4.1.2 Impoundment Period of 135m

After the impoundment of 135m, and until Sep.2006, the water level before the dam is controlled at 135m in flood season, and in dry season, it is controlled at 139m. Comparing with that of before the impoundment, some characters about the reach is changed, such as boundary conditions, manning roughness coefficient and the movement process of flow and sediment. To analyze the flow and sediment movement character in reservoir after the impoundment of TGP, the further calibration to the model is very important. In this paper, the calibration is carried out with the topography of Mar. 2003 and Oct. 2004 from Cuntan to dam, and the measured flow and sediment process from Mar. 2003 to Oct. 2004 is applied as the calculation condition. The inlet controlling station of the calculating region is Cuntan and Wulong, and the Taipingxi is confirmed as the outlet. Meanwhile, the measured dry density data of sediment in reservoir in Oct.2004 is applied into the modeling.

Through the calibration, some parameters of the model is obtained. For example, the change range of scouring coefficient is from 0.9 to 1.5, and that of the deposition coefficient is from 0.1 to 0.32. According to the measured topography between Mar.2003 and Oct. 2004, as a whole, it is silted from Qingxichang to Taipingxi(see fig.2), comparing with the measured volume of 276 million m3, the calculated value is 217 million m3, and the calculated error is 21%. In additional, the calculated process of discharge, water level and sediment concentration tally well with that of the measured value, and the error is in the permitted range.

Base on the above calculation, in this paper, verification is carried out to the modeling, in which the topography of Oct.2004 and gradation data is used, and the boundary condition is the same with that of the calibration. As a whole, the measured data appeared that it is silted from Qingxichang to Taipingxi, and the silted volume is about 29 million m^3, and the calculated conclusion indicates that the calculated value is 19% larger than the measured value (see fig.3).

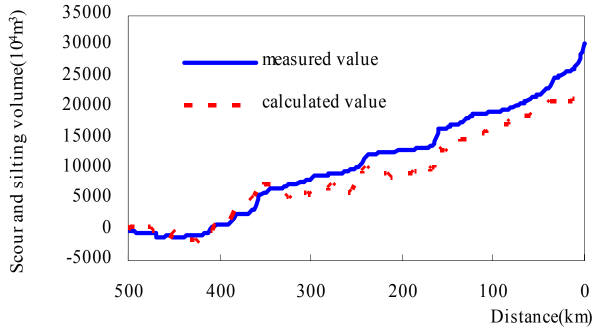

Fig.2 Comparison between calculated and measured value of accumulated scouring and deposition volume along the reach from Mar.2003 to Oct.2004 in reservoir region

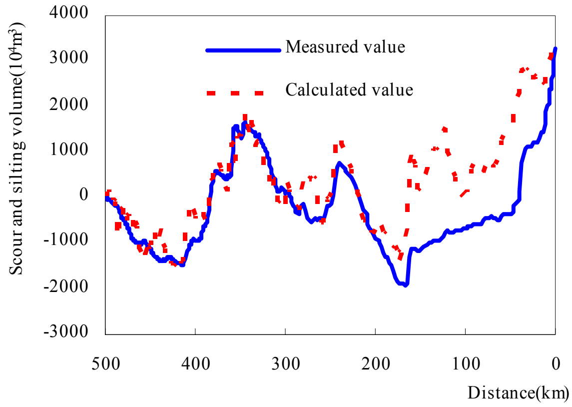

Fig.3 Comparison between calculated and measured value of accumulated scouring and deposition volume along the reach from Oct.2004 to Oct.2005 in reservoir region

4.1.3 Impoundment Period of 156m

After the flood season of 2006, TGP enters into the initial operation period, and the pool level is controlled at 144m in flood season. For the impoundment of 156m, the backwater reaches Tongluoxia, and the water level along the reach rises up accordingly, at the same time, comparing with the natural stream channel, the manning roughness coefficient, flow and sediment character changes a lot. In this paper, based on the calibration of 139m, the further verification is carried out during the impoundment period of 156m. In the calculation, the measured flow process from Jan. 2006 to Oct. 2006 is selected as the inlet condition, and the water level process of Fenghuangshan station is regarded as the outlet condition. Through the calculation and debugging, the conclusion of manning roughness coefficient is elicited in table.1, from which can be seen that some changes have been happened to the manning roughness coefficient in reservoir region, which appears as the manning roughness coefficient decreased in perennial backwater zone and increased in some local part.

Table 1 Variation of manning roughness coefficient with different pool level

Scheme / Position	Q=10000 m^3/s, Z=139m	Q= 10000 m^3/s, Z= 145m	Variation of manning roughness coefficient	Q= 10000 m^3/s, Z= 155.6m	Variation of manning roughness coefficient
Cuntan	0.041	0.039	-0.002	0.039	-0.002
Changshou	0.029	0.027	-0.002	0.030	0.001
Qingxichnag	0.063	0.065	0.002	0.055	-0.008
Nantuo	0.027	0.029	0.002	0.043	0.016
Baishatuo	0.027	0.023	-0.004	0.039	0.012
Gaojiazhen	0.022	0.026	0.004	0.039	0.017
Yangdu	0.032	0.027	-0.005	0.050	0.018
Zhongxian	0.040	0.040	0.000	0.040	0.000
Shibaozhai	0.051	0.044	-0.007	0.041	-0.010
Wanxian	0.051	0.043	-0.008	0.040	-0.011
Guling	0.061	0.047	-0.014	0.040	-0.021
Fengjie	0.061	0.046	-0.015	0.040	-0.021
Daixi	0.061	0.046	-0.015	0.040	-0.021
Beishi	0.059	0.040	-0.019	0.040	-0.019
Miaohe	0.040	0.040	0.000	0.040	0.000

4.2 1D Flow and Sediment Modeling at Downstream of Three Gorges Reservoir

4.2.1 Calculation Conditions

The calculation range of the modeling is from Yichang to Luoshan, and the total length is 409km. The inlet condition of the modeling is the measured flow and sediment process of Yichang station from Oct.1998 to 2002, the outlet condition is the water level process at Luoshan station from Oct.1998 to 2002, and the measured flow and sediment process at the control stations of flow diffluence or concentration is regarded as the so called lateral boundary condition.

4.2.2 Calibration of the model

To the 1D flow and sediment modeling from Yichang to Luoshan, the calibration includes two parts. One is the calibration of flow modeling, the other is that of the sediment modeling. The former one calculates mainly for the manning roughness coefficient along the reach, and the latter one calculates for the parameters about sediment.

1) Flow calibration

Through the measured flow and sediment data at the stage gaugings or hydrologic stations along the reach from Yichang to Luoshan, such as Yichang, Zhicheng, Shashi, Jianli, Chenjiawan, Shishou, and so on. The roughness coefficient is regulated and confirmed through debugging according to the calculation error.

2) Calibration of sediment concentration and riverbed deformation

Based on the simulation of flow modeling, the topography of Oct.1998 is regarded as the initial state, the accumulative scouring and deposition and its distribution along the reach is simulated, the comparison of calculated and measured value from Oct.1998 to 2002 can be seen from fig.4, and the conclusion indicates that the calculated value tallies well with the measured value. Through the simulation, the parameters in the model is elicited as the following: the change range of scouring coefficient is from 0.28 to 1.89, and that of the deposition coefficient is from 0.12 to 0.96.

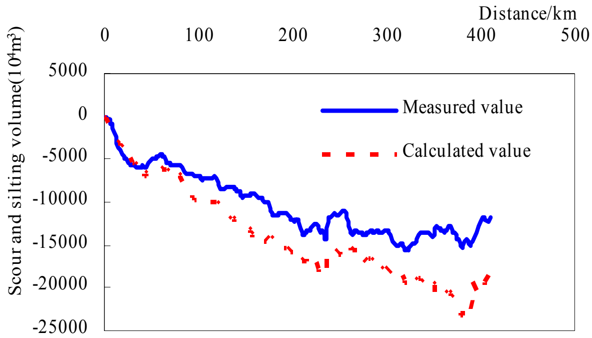

Fig.4 Comparison of calculated and measured value of accumulated scouring and deposition volume along the reach from Oct.1998 to Oct.2002 from Yichang to Luoshan

4.2.3 Verification of the modeling

Based on the above calibration, the topography data of Oct.2002 and Oct. 2005 is adopted to verify the modeling. According to the topography of Oct.2002 and Oct. 2005, it can be elicited that the riverbed scouring is happened from Yichang to Luoshan, and the scouring volume is about 331 million m3, and the calculated value is 48% less that the measured value.(see fig.5)

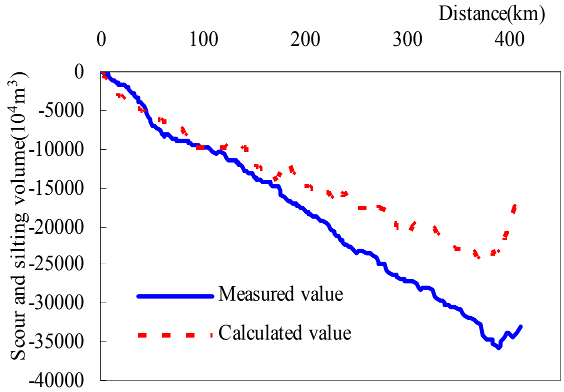

Fig.5 Comparison of calculated and measured value of accumulated scouring and deposition volume along the reach from Oct.2002 to Oct 2005 from Yichang to Luoshan

4.3 Main Problems

Although the Flow and sediment models are widely applied into many fields, many problems in models need to be improved, including sediment carrying capacity of different grain sizes, bed load transportation rate, exchange among suspended load, bed load and bed material, manning roughness coefficient. Especially for computing the sediment transport, because the sediment transport formulas having been developed are mostly empirical or semi-empirical and have large discrepancy among them, their calibration and verification are very important. Furthermore, there are different viewpoint for the statistic data. For example, for calculating the amount of scouring and deposition, two methods are used generally, one is sediment transport balance method, and the other is topographic change method, however, the results of two methods are different, even at some time, it is almost on the contrary, In the reach from Shashi to Jianli, based on the topographic change method, the scouring amount of reach is about 0.0495 billion m3, but using the sediment transport balance method, the reach is silted and the amount is about 0.163 billion m3. These problems should be solved in further research.

Table 2 Comparison between sediment transport balance and topographic change methods of the scouring and deposition volume

Reach	Length (km)	Scouring and deposition volume ($10^4 m^3$)		
		Topographi change method	Sediment transport balance method	Relative error(%)
Yichang to Shashi	174.5	-9585	-4889	-49%
Shashi to Jianli	222.8	-4951	16296	—
Jianli to Luoshan	18.3	3225	9111	—
Yichang to Luoshan	415	-11311	20519	—

5 2D Flow and Sediment Modeling in Changjiang River

2D flow and sediment modeling is mostly used to study the scouring and deposition in local reach during one short period of time. In this paper, according to the different river regime and scouring or deposition character in different kinds of reach, the Tunaozi, Shashi and Wuhan reach are regarded as the example, the scouring and deposition process is simulated in the meandering river reach near Shashi city and the braided river reach near Wuhan city at the middle-downstream of Changjiang River.

5.1 Studying and Application of Flow and Sediment Modeling in Backwater Region

Tunaozi reach is one of the three severe sediment deposition reach in Changjiang River, which lies in the fluctuating backwater area of the Three Gorges Project and about 455km away from the Three Gorges project. It is a meandering channel and 3km in length from Caijiatan to Lusipan. In the upstream, the Qingxichang gauging station is about 17km away from this reach. During the impoundment period of Three Gorges Reservoir, the reach lies at the fluctuating backwater area of TGP. To research the sediment transport character in this reach, using the 2D flow and sediment model, the sediment scouring and deposition is calculated, the model is mainly used to simulate the sediment transport process during the falling period of the reservoir.

5.1.1 Calculation Conditions

According to the different character of flow and sediment process, and considering different scouring and deposition character of this reach. In this paper, four periods of time is selected for the calibration and verification of the model, one is the period of low level from Mar.6 2004 to Mar.18 2004, in this period, the topography of Mar.2004 is regarded as the initial state, the second one is the period of high level from Mar.18 2004 to April.30 2004, the third one is the verification period of low level from April.30 2004 to May.25 2004, the last one is the verification period of high level from May.25 2004 to Jun.15 2006.

In each calculation period of time, the measured flow and sediment process of Qingxichang station is regarded as the inlet condition, the water level process of Nantuo station is regarded the outlet condition. The whole length of the calculation region is 10km. The computational mesh consists of 150×60 cells. The Grid arrangement in calculation area can be seen in fig.6.

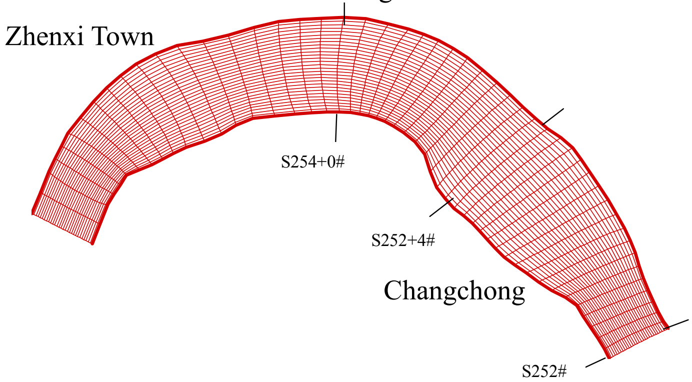

Fig.6 Grid arrangement in calculation area

5.1.2 Conclusion Analysis

The calculated conclusion can be analyzed as three parts mainly. One is scouring and deposition volume along the reach, one is the distribution of suspended load concentration along the sections, and the last one is transverse deformation of typical sections.

1) Accumulative scouring and deposition volume along the reach

Tab.3 is the comparison of scouring and deposition volume along the reach of calibration and verification, from which it can be seen that the calculated scouring and deposition volume along the reach tallies well with the measured value, and the calculated precision is good.

Table 3 Comparison of scouring and deposition volume along the reach of calibration and verification

	Calculation period of time	Measured scouring and deposition volume (10^4t)	Calculated scouring and deposition volume (10^4t)	Calculated relative error (%)
Calibration in the period of low level	From Mar.6 to Mar.18	-67.1	-59.0	13.0
Verification in the period of low level	FromApr.30 to May.25	-349.3	-308.5	13.2
Calibration in the period of high level	From Mar.18 to Apr.30	132.6	108.7	18.0
Verification in the period of high level	From May.25 to Jun.15	179.1	146.0	18.5

2) Distribution of suspended load concentration along the sections

Tab.4 is the comparison of measured and calculated sediment discharge and sediment diversion of calibration and verification at the section S252+4 and S254+0, from the table we can see that the sediment diversion of right branch is 87%, which indicates that the right branch is the main branch, and the difference of the calculated and measured value is less than 5%. So it is obvious that the calculated precision is very high.

Table 4 Comparison of measured and calculated sediment diversion of calibration and verification period of time

Time	Measured sediment discharge (kg/s)		Measured sediment diversion (%)		Calculated sediment diversion (%)	
	Left-branch	Right-branch	Left-branch	Right-branch	Left-branch	Right-branch
Mar.18	5.88	115.5	4.9	95.1	7.1	92.9
May. 20	102	726	12.3	87.7	7.0	93.0
May. 21	265	2060	11.4	88.6	9.2	90.8
May. 26	129	1580	7.5	92.5	9.9	90.1
Jun. 12	160	1480	9.8	90.2	7.2	92.8

3) Transverse deformation of typical sections

There are 11 typical sections is arranged in Tunaozi reach, and to analyze the reasonableness of the calculation result about the deformation of the cross sections, with the example of section S252+4, the comparison between the calculated and measured value can be seen from fig.7. It can be seen that the calculated value tallies well with the measured value, and the result can reflect the basic discipline of “deposition in flood period and scouring in dry season”. From Mar.6 to Mar.18, which is the calibration period in low level, for the falling of water level, the flow velocity increased, and the riverbed is scoured. For example, the main channel near the right bank and middle channel is scoured to some extent, and the scouring range is from 0.1m to 0.3m. From Mar.18 to Apr.30, which is the calibration period of high level, at this period, for the pour level rose up at the end of the low level period, the flow velocity decreased, and the sediment deposited in the reach. For example, at the section named S252+4, sediment deposition happened to the riverbed where the altitude is less than 132m, and the deposition thickness in main channel is about 0.9m, which is the thickest.

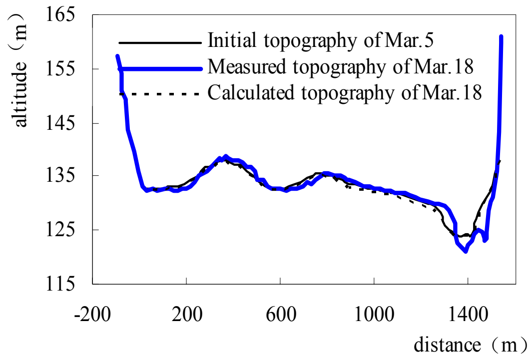

Fig.7 Comparison between measured and calculated deformation at S252+4 of Tunaozi reach (calibration period of low level)

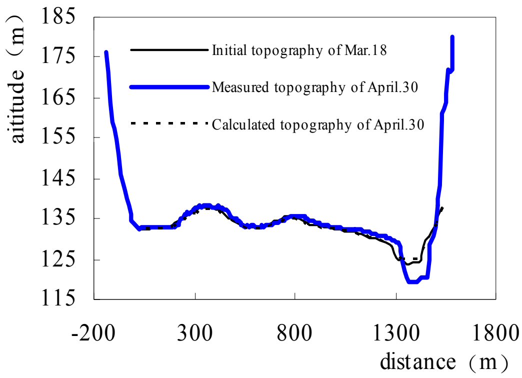

Fig.7 Comparison between measured and calculated deformation at S252+4 of Tunaozi reach (calibration period of high level)

5.2 Studying and application of flow and sediment modeling at meandering braided reach

After the impoundment of dam, the most important effect on the lower reache of the dam is the reduction of sediment load, which results in sediment-starvation of the flow and consequently in fluvial process. In Shashi reach, the main flow line migrates frequently and the fluvial process of shoal and beach is complex. In the paper, taking this reach as example, the capability of model to simulating flow and sediment transport is tested.

5.2.1 Boundary conditions

The simulated reach is 30km in length from Chen jiawan to Guanyinshi. The computational mesh is consisted of 230×80 cells. To simulate the flow and sediment transportation exactly, the field data including instantaneous water surface, velocity, sediment concentration, components of bed material and riverbed topography observed by BOH during 1996～1998 are used to calibrate the parameters and verify the model.

5.2.2 Result Analysis of Calibration and Verification

The field data during 1996~1998 is used to calibrate the parameters. Fig.8 shows that the comparison of the calculated and measured amount of scouring and deposition in the reach from 1996 to 1998 is in good agreement. The calculated volume of scouring is 0.0147 billion m3and the measured volume is 0.0159 billion m3. The error is only 7.7%.

Based on the parameters calibration, the model is verified using the field data from 1998 to 2001. Fig.9 shows the comparison of the calculated and measured distribution of scouring and deposition in the reach. The calculated volume of erosion is 7,160,000 m3and the measured volume is 8,090,000 m3. The error is only 11.5%,which shows that the model can simulate fluvial process in this reach very well.

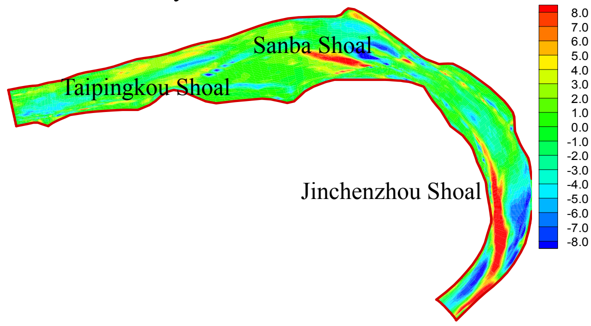

Fig.8-1 Measured horizontal distribution of scouring and deposition at Shashi reach (from 1996 to 1998)

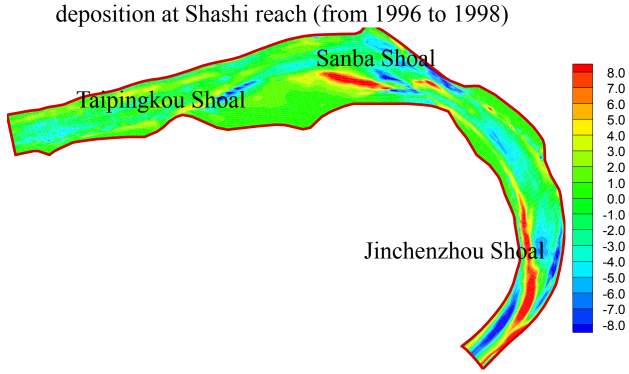

Fig.8-2 Calculated horizontal distribution of scouring and deposition at Shashi reach (from 1996 to 1998)

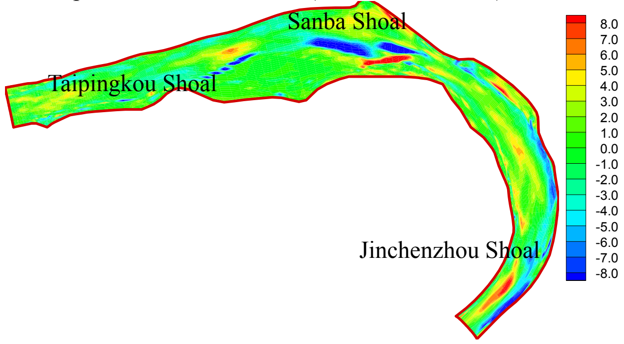

Fig.9-1 Measured horizontal distribution of scouring and deposition along Shashi reach (from Dec.1998 to Oct.2001)

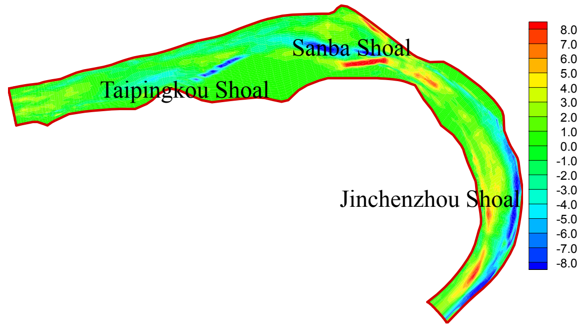

Fig.9-2 Calculated horizontal distribution of scouring and deposition along Shashi reach (from Dec.1998 to Oct.2001)

5.3 Studying and Application of Flow and Sediment Modeling in Straight Braided Reach

Based on the above research, to verify the precision of model when it is used in straight braided reach, in this paper, Wuhan reach is regarded as the research object, the flow and sediment modeling of this reach is carried out.

5.3.1 Boundary Conditions

The calculation region is from Wuhan to Yangluo, and the total length is about 28km. The computational mesh consists of 450×512 cells. Before the modeling, the two groups of hydrometry section is selected, one is in Apr.10 2005, the other is in Jul.20 2005. Through the calibration and verification of the parameters in the modeling, the result indicates that the calculated value tallies well with the measured value.

5.3.2 Riverbed Scouring and deposition of Calibration and Verification

To simulate the flow and sediment transportation exactly, the field data including instantaneous water surface, velocity, sediment concentration, components of bed material and riverbed topography observed by BOH during 2002～2004 are used to calibrate the parameters and verify the model. Through the simulation and calibration, the parameters of the model is confirmed, such as the change range of deposition parameter is from 0.15 to 0.70, the scouring parameter is from 0.6 to 1.6, which is very close with the theory value, further more, the simulated result shows that the calculated volume of erosion is 0.161 billion m3and the measured volume is 0.0151 billion m3. The error is only 6.3%, which is in reasonably good agreement.

In the verification period, which is from 2004 to 2005, the calculated volume of erosion is 0.0139 billion m3and the measured volume is 0.015 billion m3, and the error is only 7.5%, which is fit with the precision requirement.

6 Conclusion

Sediment problem is one of the key technical issues of TGP. After the TGP was put into operation, large amounts of sediment will be deposited in reservoir and serious scouring will be happened to the riverbed at the downstream. In this paper, the observation region and some of the sediment monitoring results about of COH, which offered abundance data base and the most reliable accordance for flow and sediment management is introduced, then, based on the theory of hydraulics and river dynamics, and by making the best use of abundant prototype monitoring data, the 1D flow and sediment modeling of reservoir region and downstream, 2D flow and sediment model is developed. Through the verification by prototype monitoring data, the conclusion is elicited that the developed model can provide some technical supports to the prototype monitoring of BOH, and it has quite important significance for mastering the rule of riverbed evolution and the flow and sediment transportation.

Acknowledgements

This work was supported by National 973 Program (Grant No: 2003CB415200).

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