Morphological Evolution of the Scour Pit After Danjiangkou Dam Heightening Project

Ying Chen, Xian-zheng Wang, Hong-xia Zhang and Zhi-gang He
Hanjiang Bureau of Hydrology and Water Resources Survey, Changjiang Water Resources Commission, China

Keywords: Danjiangkou Dam Heightening Project, Scour Pit, Mophological Evolution, Empirical Orthogonal Function, Autumn Flood in Hanjiang in 2021.

Abstract: Danjiangkou Reservoir is the largest artificial fresh water lake in Asia, the water source of the middle route of the South-to-North Water Diversion Project. This paper analyzes the process and the reasons of the scour pit under Danjiangkou Dam,then particularly analyzes its morphological evolution after the Autumn flood in Hanjiang in 2021. After the flood in 2021, there are big increases in the range and depth of the scour pit. The results shows that the area of 75m contours of the spit increased from about 1.2×10^4 m^2 to 1.4×10^4 m^2. Correspondingly, sediment volume of the scour pit drastically decreased, especially the volume between the 75m and 60m contours. Furthermore, the Empirical Orthogonal Function (EOF) is applied to analyze the morphological evolution of the scour pit under the Danjiangkou dam. The topographic data are separated into independent spatial eigenfuntion along with temporal eigenfuntion by the EOF analysis. The first three modes provide a detailed, comprehensive description of the morphological evolution of the scour pit. The first mode accounts for 58.5% of the overall evolution patterns, it shows the trend of the scouring downstream of the scour spit. The second mode reflects that the scour pit achieved a dynamic balance of sediment. And the third mode indicates that the sediment source of the center of the scour pit. This paper explains that the EOF analysis can be used into the evolution of river-bed, and provides the theory basis for the safety operation of the Danjiangkou dam.

1 INTRODUCTION

Riverbed erosion and accretion are a major part of the evolution in which many researchers are very interested. Researchers have never stopped studying on it (Nitsche et al., 2006 and Hu et al., 2009). Research results can be used to analyze the variation trend, so that appropriate measures can be taken to protect hydraulic structure or riverbed and avoid harm. Due to the impact of the flood release from the dam, scouring below the sluice continues, and it is subjected to severe erosion damage(Li et al, 2003). There are many factors leading to scour pits under dams. A submerged hydraulic jump downstream of an apron tend to cause the evolution of local scour(Akiyama et al., 2010), resulting in the shape of the scour pits similar. The geometrical similarity of scour pits downstream of a sluice gate is related to geological factors(Hamidifar et al., 2017).

The establishment of water conservancy projects in river channels changes the characteristics of the flow field, and the energy of the discharge under the spillway is much larger than the normal specific energy of the flow in the downstream river, so the scouring damage to the downstream river bed is more obvious.(Shang., 2012))

The downstream river bed erosion is an engineering issue of wide concern in the hydraulic engineering industry. Physical and Numerical models have been widely employed to explore the characteristics of river bed erosion downstream of the dam. Zhang and Liu (2020) developed a physical model, finding that the special station, such as downstream apron and the right bank will be scoured under the condition of the special flow. The research shows the shape optimum design of overflow weir is a factor affecting the location of scour.

Hao and Li(2019) build the overall hydraulic model test of Chaiping Hydropower station, draw a conclusion of the size of the hydropower station is optimized to weaken the downstream riverbed scour and reduce the influence on the overall stability of the dam, so that the hydropower station can meet the operation requirements of the project.

A 2D water-sediment mathematical mode is established by Zou and Tang(2018), for calcutating

Chen, Y., Wang, X., Zhang, H. and He, Z.
Morphological Evolution of the Scour Pit After Danjiangkou Dam Heightening Project.
DOI: 10.5220/0012024900003536
In *Proceedings of the 3rd International Symposium on Water, Ecology and Environment (ISWEE 2022)*, pages 308-318
ISBN: 978-989-758-639-2; ISSN: 2975-9439

the possible downstream scour of the dam for the project to be caused after the complete of Bazizui Project.Meanwhile, in order to accurately predict the range and depth of scour pits in downstream riverbed, a numerical model of local riverbed scour was established based on the dynamic grid technology in Fluent software by Fan(2021).

Based on the theoretical analysis and model simulation results of riverbed scour under dam by many scholars, it can be seen that the main influencing factors of local scour under dam are hydraulic factors such as the shape of overflow weir and the size of downstream discharge. Taking Danjiangkou Dam as an example, this paper discusses the characteristics and evolution trend of scour under danjiangkou dam after its heightening, which provides technical support for dam operation.

Danjiangkou reservoir covers an area of 95,200 km^2, accounting for 60% of the total area of the Hanjiang River basin. Danjiangkou reservoir is the largest artificial fresh water lake in Asia, the water source of the middle route of the South-to-North Water Diversion Project, the national first-class water source protection zone, the important wetland protection zone in China, and the national ecological civilization demonstration zone. Danjiangkou dam has attracted extensive attention both from both inside and outside of the industry since it was set up. Many scholars have also conducted a large number of studies on the formation and evolution mechanism of riverbed under the Danjiangkou Dam, and analyzed the morphological evolution of scour pits(Duan et al., 2007 and Zhang et al., 2008).

For Danjiangkou dam with the characteristics of high water head, large discharge, the problems of erosion damage are exceedingly serious. Virtually, downstream riverbed has formed many scour pits since the reservoir operation in the initial period of the project. According to statistics, the duration of flood charge in the deep hole 9-11 dam section is the longest, the downstream bed received the certain degree of flushing, and formed a prominent pit, now the scour shows a trend of move to the upstream and the East direction (Wang et al., 2007).

This paper mainly carried on the concrete analysis to the scour pit under 9-11 dam section, and analyzes the process and the reasons of the scour pit under Danjiangkou Dam, then particularly analyzes its morphological evolution after the Autumn flood in Hanjiang in 2021. Therefore, the objectives in this contribution are as follow: (1) to quantitatively explore the morphological changes of scour spit in area, sediment volume variations in different phase; (2) to interpret the underlying factors associated with morphological evolution and analysis the trend of the scour pit.

2 STUDY AREA

2.1 General View of Danjiangkou Dam

Danjiangkou Reservoir is located in Xichuan County of Henan Province and Danjiangkou City of Hubei Province. Danjiangkou Reservoir is a large-scale artificial reservoir with functions of water supply, flood control and power generation as well as irrigation and breeding. It is a multi-year regulating reservoir. The initial project of Danjiangkou Dam was started in September 1958 and completed in 1973. In the past 30 years, it has played a great role and achieved remarkable economic and social benefits. Then the Danjiangkou Dam heighting project started in September 2005 and completed in 2013. In present, Danjiangkou reservoir dam has a total area of 1050km^2 with a storage capacity of 29.05 billion m^3 when the normal water level is up to 170m.

Danjiangkou dam is a wide-slit gravity dam, which consists of dam sections 1-44 according to the distribution characteristics of buildings a. According to the frequency of operation, the spillway structure is divided into two parts, normal spillway and extraordinary spillway, which are arranged in the dam section 8- 24. Among them, the dam sections 8-13 is the deep hole dam section with a total length of 144m, which are composed of 11 deep spillway holes. Dam sections 14-17 and 19-24 are overflow dam sections with a total of 20 open overflow holes of 8.5m in width. There are 8 holes in dam sections 14-17 as overflow holes, 12 holes in dam sections 19-24 as infrequently used overflow holes. Dam section 18 is a longitudinal cofferdam with no-overflow section (Wang et al., 2002).

2.2 Morphology of the Scour Pit Under Danjiangkou Dam

According to the structural arrangement of the spillway sections, it can be seen that the downstream riverbed located at No. 8-13 dam sections and No. 9-17 dam sections are vulnerable to be flushing. In addition, combined with the statistics of the date of the opening and closing of the gates (Table 1), the duration of the flood discharge takes the longest in the 9-11 dam section and the 15-16 dam section, so the scouring situation of the downstream river bed in this section needs to be focused on. With time the riverbed has shown the water carved out a large scour pit downstream of the 10-17 dam section. The location and form of the scour pit are shown in Figure 1.

Combined with the morphology of scour pits and the exploration of riverbed geology under the dam (Cai et al., 2002), it can be seen that the scour pit is washed along three geological fault zones in the plane at the same time. In this paper, three profile lines are selected for qualitative analysis of scouring and silting in the fault zone. The following sections will elaborate on these ideas. The profile lines are arranged based on the erosion zone and the positions of the three erosion zones are shown in Figure 1.

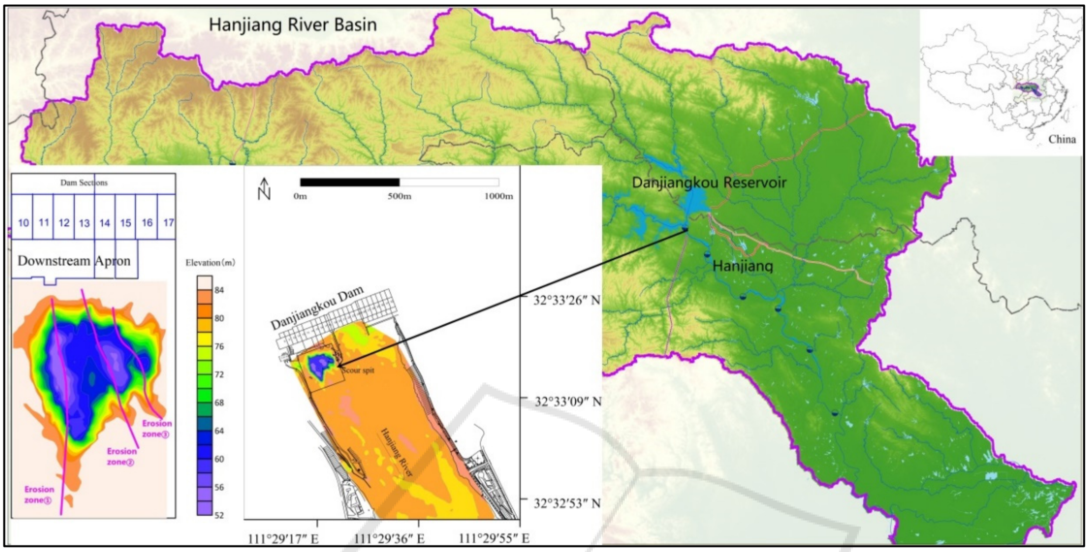

Figure1: The location and form of the scour pit of the Danjiangkou Dam.

3 FORMMATERIAL AND METHODS

3.1 Material

Topographic survey has been widely used to explore river bed evolution. Based on digital contour DEM, the sedimentary erosion characteristics of the scour pit were studied. Topographic data are collected from topographic maps from 2005 to 2021. All scales are 1:500, and Danjiangkou dam axis coordinate system is adopted in the maps. Then kriging interpolation technique is used to interpolate the digital data into a grid with a spatial resolution of 2.5m × 2.5m to reduce the interpolation error. In order to investigate the morphological evolution of scour pits, the data of discharge flow, water level difference between the upper and lower reaches and opening position of dam sections are collected and analyzed. The hydrological data are all from the Hanjiang Bureau of Hydrology and Water Resources Survey.

Table2 shows the statistics of flood discharge from 2005 to 2021. Wusong height datum of China is determined in the paper.

3.2 Methods

In order to analyze the spatial and temporal correlations of elevation and explore possible evolution patterns in different periods, the multivariate analysis technique Empirical Orthogonal/Eigen Function (EOF) is used in this study. Empirical Orthogonal Function analysis (EOF) method. EOF analysis was first introduced into meteorological problem analysis (Yosef et al., 2017). However, in recent years, many scholars have applied this method to study topographic evolution (Yuhi et al., 2017, Xia et al., 2005 and Horrillo-Caraballo et al., 2009). Most of these scholars analyze the evolution of typical sections by processing topographic profile data, and some scholars have applied this method to the evolution analysis of the whole topographic region (Beckers et al., 2003 and Dai et al., 2015). Through the research of many scholars at home and abroad, it is known that empirical orthogonal function analysis methodcan be used to explain the causes of river bed evolution. When EOF is used for terrain analysis, feature vectors correspond to spatial samples, and principal components correspond to time coefficients, so it can be called EOF method for time-space separation. Its principle is to decompose the variable field that changes with time into several mutually independent orthogonal modes through spatio-temporal decomposition, and each mode has a corresponding space function and time function. The first several modes, which account for a large proportion of the total variance of all variables at the original space point, can be used to summarize the most important information of the factor field. Therefore, we can replace the study by studying the rules of the change of these major components with time and better explain the time changes of the field. The advantage is that it can decompose the irregularly distributed sites in a definite limited area, and the result obtained by decomposition has more complete physical significance, and can better reflect the basic structure of the appearance.

In this paper, topographic data under Danjiangkou Dam in recent years are given in the form of elevation matrix A after anomaly processing: $A=X_{m\times n}$. Where m represents spatial data point and n represents time series length. Then, the EOF analysis method is applied to decompose the matrix

$X_{m\times n}$ into orthogonal spatial characteristic function V and time characteristic function Z.

$$X = VZ \tag{1}$$

V is the spatial characteristic function, reflecting the spatial variation of the scour pit area; Z means time characteristic function, reflecting the change of scour pit elevation over time.

The specific decomposition method is as follows:

(1) Calculate the product of X and XT to obtain a matrix R composed of correlation coefficients

$$R = X \times X^T \tag{2}$$

(2) Calculate the eigenvalues of the correlation coefficient matrix R (λ_1, λ_2... λ_m) and the eigenvector Vmxm, both of which should satisfy.

$$R = V \Lambda V^T \tag{3}$$

Λ represents a diagonal matrix composed of the eigenvalues of R.

$$\Lambda = \begin{bmatrix} \lambda_1 & 0 & \cdots & 0 \\ 0 & \lambda_2 & \cdots & 0 \\ \cdots & \cdots & \cdots & 0 \\ 0 & 0 & \cdots & \lambda_m \end{bmatrix} \tag{4}$$

Arrange the eigenvalues in non-ascending order. Each eigenvalue has a list of eigenvectors corresponding to it, also known as EOF. The eigenvector corresponding to the k eigenvalue λ k is the k column of the eigenvector matrix V.

$$EOF_k = V(:,K) \tag{5}$$

V is projected onto the matrix X composed of terrain data, so as to obtain the corresponding time coefficients of all spatial feature vectors

$$Z = V^T \times X \tag{6}$$

(4) Calculate the contribution rates of each mode. The formula for calculating the corresponding contribution rate Rk of the k is as follows:

$$R_k = \frac{\lambda_k}{\sum_{i=1}^{m} \lambda_i} \left[k = 1,2,..., p(p \le m)\right] \tag{7}$$

(5) The cumulative contribution rate of each mode can be obtained according to the formula below

$$G = \frac{\sum_{i=1}^{p} \lambda_i}{\sum_{i=1}^{m} \lambda_i} (\mathrm{P} < m) \tag{8}$$

Through the numerical calculation software MATLAB according to the EOF analysis of the calculation principle of programming, calculate the time characteristic function and space characteristic function of each mode, as well as the corresponding eigenvalue. Therefore, elevation change of scour pits under Danjiangkou dam can be transformed into a series of characteristic values to reflect the pattern of its morphological changes.

Table 1: The duration of the flood discharge of the dam section in 2017-2021.

Time (h)	Dam Sections												
	8	9	10	11	12	14R	14L	15R	15L	16R	16L	17R	17L
2017	89.5	140.0	547.5	558.1	454.0		257.1		352.0		413		
2018	52.2						139.5		434.9		242		
2019	90.2	110.8	115.3	15.7		50.9	59.4	22.9				27.8	

2020	23.0	109.2	167.8	3.0	24.5			171.0		142.7			
2021	596.8	866.1	1185.5	1043.8	577.9	115.1		913.3		593.4		46.6	375
Sum	851.8	1226	2016.1	1620.6	628.8	166.0	456.0	1110.2	796.9	736.1	655	74.4	375

Table 2: The flood discharge data of the Danjiangkou Dam in 2005-2021.

Year	Maximum reservoir water level(m)	Maximum water level under the dam(m)	Water Head Difference(m)	Maximum discharge （m^3/s）	The number of discharge sluice hole(deep/overflow)		Days of flood discharge
2005	156.95	95.99	60.96	14300	9	5	32
2007	151.15	92.66	58.49	6870	6	1	27
2009	153.04	91.35	61.69	2450	1		16
2010	154.95	93.71	61.24	7280	7	2	55
2011	157.29	95.78	61.51	12800	9	4	29
2012	155.44	90.91	64.53	2460		2	6
2017	167.00	94.70	72.30	8040	4	4	34
2018	165.43	91.77	73.66	3380		4	23
2019	166.51	94.32	72.19	7260	5	3	10
2020	164.7	91.89	72.81	3680	1	2	19
2021	170.00	95.03	74.97	11100	5	4	75

4 EVOLUTION CHARACTERISTICS OF SCOUR PITS UNDER DANJIANGKOU DAM

Based on topographic data of the Danjiangkou dam from 2005 to 2021, DEM model was established to analyze the evolution characteristics of scour pits under the Danjiangkou dam in recent years.

4.1 Horizontal Changes

According to the profile of scour pits, scour pits are basically extending downstream along the three scour zones. In order to qualitatively analyze the scour and silt shape of scour pits, scour pits are divided into three levels according to contours of 60m, 75m and 85m for analysis.

Changes in the area of the scour pit in the 60m, 75-60m and 85-75m contours can be seen in figure 2. The 60m contours area can be used to describe the variation of scour and silting at the bottom of the pit, 75-60m can reflect the evolution at the slope of the pit, and 85-75m was set as the sediment scour and deposition at the boundary of the pit. Considering the implement of the Danjiangkou dam heightening project in 2013 and intensive autumn flood in 2021, the temporal variations of the morphology can be generally divided into three phases: before the heightening project (phase Ⅰ: 2005~2013), after the heightening project (phase Ⅱ: 2013~2019) and through the autumn flood in Hanjiang in 2021 (phaseⅢ: 2019~2021). Elevation changes according to the sediment erosion and accretion in each period in figure 3, which the 75m contour line in 2005 can better showcase the specific variation position of the scour pit (bottom or slope).

During the phase Ⅰ :In 2005-2006, the maximum discharge flow reached 15,100m^3 /s. The area at the pit bottom increased significantly with the scour area at 60m contour of 1619m^2. Meanwhile, the area of 75m contour almost remained unchanged, with the area of the 85m contour line decreased slightly. It shows that the scour in this period mainly downward scours. In 2006-2013, there was a small change in the area surrounded by contour lines below 60m and 75-60m, while the area of 85-75m contour increased significantly with an area increment of 1828m^2, indicating that scour pits were mainly developed and expanded to the periphery during this period.

During the phase Ⅱ: in 2013-2015, changes in the area of scour pit were not evident. During this period, discharge was decreasing, and scour pit basically did not develop further. After the Danjiangkou Dam heightening project, experienced the autumn flood in Hanjiang in 2017, the area of 85-75m and below 60m contours decreased, while the range between 75-60m showed an increasing trend, indicating that the anti-scour layer had gradually formed at the pit bottom during this period, and there was no further scouring. The scour sand at the pit tail fell back to the pit bottom, leading to accretion of the pit bottom. As a result, the range of 60m contour is reduced, and the scour tends to extend downstream and to the east and west sides, and the larger the downstream discharge, the larger the range of expansion.

During the phase Ⅲ: in 2019-2021, Hanjiang River experienced the autumn flood in 2021. The discharge flow was as high as 11100m^3/s with the water head difference was 74.97m, the highest in recent years. The water level in front of the dam was 170m, reached normal water level for the first time. This means the jet trajectory length increased. The effect goes further downstream. Therefore, remarkable scour zone can be seen in the tail of the scour pit（tail means downstream part of the scour pit).

In order to study the elevation and position changes of the lowest point of the scour pit, the 60m contour line and the position and elevation of the lowest point in 2005, 2011, 2017, 2019 and 2021 were superimposed and plotted in figure 5. As can be seen from the figure, the 60m contour line is separated into left and right parts after 2019, while the middle part is silted, indicating that the scour pit develops along the scour zone. The main scour site is located near the right river bed of the scour pit, and the minimum elevation of the scour pit is also distributed along the scour zone and presents a downward trend year by year. After the implementation of the Danjiangkou dam heightening project, the minimum elevation of the scour pit does not move down further, but the elevation is still reduced by 3.6m in 2021, which is mainly related to the magnitude of the discharge flow.

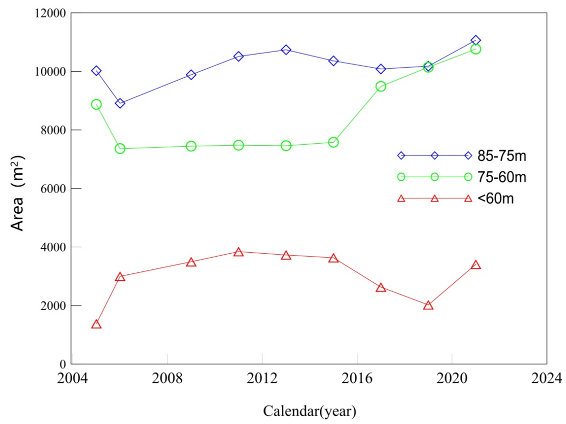

Figure 2: Changes in the area of the scour pit in the 60m, 75-60m and 85-75m contours.

4.2 Longitudinal Changes

Sediment volume of the scour pit was calculated to explore the erosion or deposition regime during the 2005-2021. The change of sediment volume, as well as the area, was explored by dividing into three levels (Figure. 4).

Changes in sediment volume displayed that the region below the 85m contour received a net erosion with the amount of 5.18×10^4 m^3 over the phase I (2005-2013), with an average erosion rate of 6.48×10^3 m^3/yr. Furthermore, the amount of sediment erosion during the 2006~2009 in the zone was the most dominant over the phase I, which amount was $2.28\times10^4m^3$, accounting for 44.0% of the period. In vertical, the erosion mainly occurred in the area below 60m with the rate was $1.03\times10^4m^3/a$ in 2005-2006. During this period, the maximum flood discharge was 15100m^3/s, which impact played a dominant role on the scour spit evolution below the 60m contour. The rate of erosion below the 60m contour in 2005-2006 was obviously higher than the other periods of the phase I. However, the flood discharge in 2009-2011 was as high as 13000m^3/s, but the elevation of the bottom of the scour pit did not decrease further. In summary, the period from 2005 to 2011 was the main development period of scour pit. The initial stage expresses the continuous downward flushing of the scour pit which the erosion occurs mainly below the 60m contour. Then the second stage shows that the anti-scour layer gradually appears at the bottom of the pit, which leads to the downward flushing rate of the bottom of the pit slowing down, and the effect of the discharge on the surrounding slope becomes relatively obvious. The sediment volume in 2011-2013 was relatively in equilibrium and even slight sediment accumulation was found in the period.

After the execution of heighting project, as a result of the decrease of the discharge, the scour pits turned into silting with the amount of $0.67 \times 10^4 m^3$ in 2013-2015. Subsequently, with autumn flood in 2017, Danjiangkou dam applied 167m high water level for the first time after heighten the dam with the discharge was $7750m^3/s$, the difference between the upper and lower water levels of the dam reached 72.93m. The increase of water flow resulted in the scouring trend of the scour pit, but the area from 60m to the bottom of the pit still showed a trend of silting, which was mainly caused by the sediment at the slope of the pit falling back to the bottom. In 2017-2019, the fluctuation of area alteration was much insignificant due to the weak hydrodynamics.

During the period of 2019 to 2021(phase Ⅲ), autumn floods occurred in the Hanjiang, and the flood discharge days of the sluice reached 75 days, and the discharge exceeded 10,000 m^3/s. With the hydrodynamic factors changed, the scour pit under the dam presents a scouring trend, mainly within the range of 75-85m. As shown in figure 3, the scour is mainly located on the downstream tail slope. To sum up, the morphology of the scour pit is unstable.Considering the increasing discharge, the scour pit in the morphological changes has the potential to show an increasing trend. The scour position of the scour pit is prone to locate the slopes on both sides and downstream.

The section changes of the three scour zones in the scour pit over the years were analyzed, as shown in figure 6. As can be seen from the figures, scour basically develops along the erosion zone①. In 2011, the scour depth reached the maximum with an elevation of 52.6m, which was more than 6m lower than that of the same area in 2005. Subsequently, the erosion zone①did not wash down further, and the lowest elevation gradually increased, but the slope near the downstream showed a trend of continuous scour. With an elevation of 73m, the distance in 2019 was scrubbed nearly 20m compared with that in 2011. The scour zone mainly showed downward scour from 2005 to 2011, downstream scour from 2011 to 2019, and the scour zone mainly showed downward scour and slope collapse from 2019 to 2021, with a collapse amplitude of 11m.

The lowest point of erosion zone②occurred in 2013, which was 54.5m. Then the pit bottom showed a trend of backsilting with erosion zone②, and the downstream slope showed a trend of scour, especially in 2021, the slope scoured down about 15m. The erosion zone③ is relatively higher than the other two, with the lowest elevation of 58.7m. The scour range at the bottom of the pit and on both sides of the slope is not large. The maximum scour occurred in the transverse direction in 2009, which is relatively stable in recent years. To sum up, scour mainly occurs in the area of erosion zone①, while erosion zone ② and ③ is relatively weak. The amplitude and morphological changes of the scour pit are strongly correlated with the discharge and opened dam sections of the Danjiangkou dam.

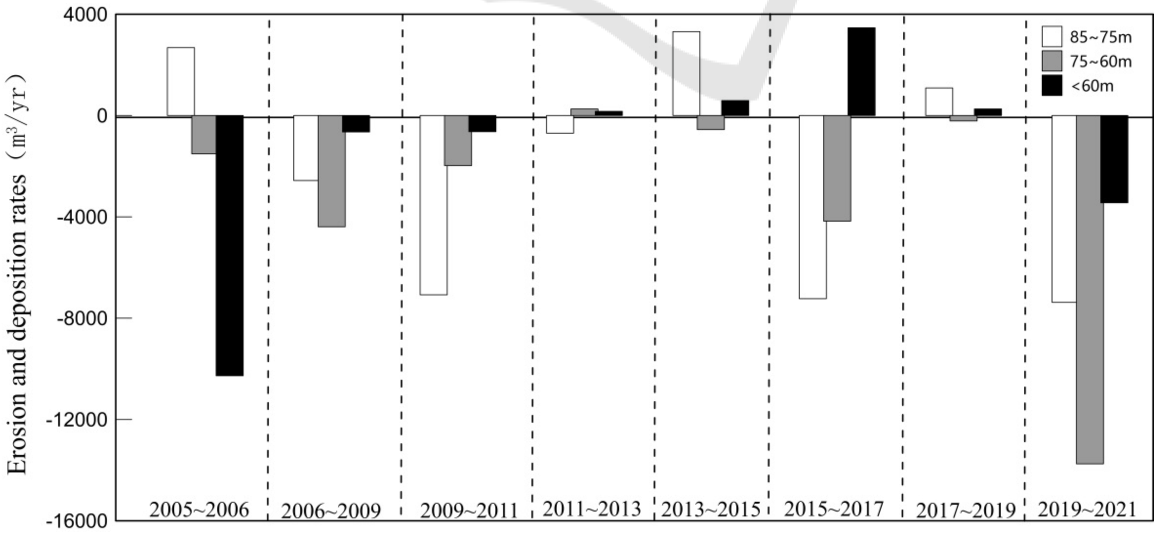

Figure 3: Elevation changes of the scour pit. Positive values indicate net deposition while negative values indicate net erosion.

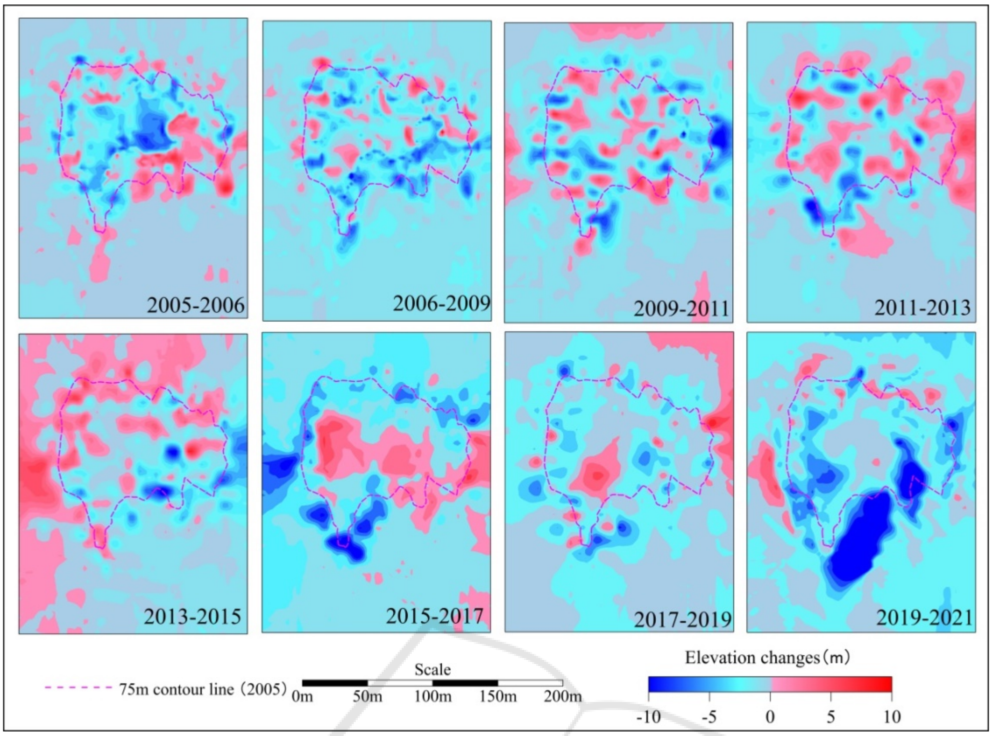

Figure 4: The erosion (negative values) and deposition (positive values) rates of the scour pit.

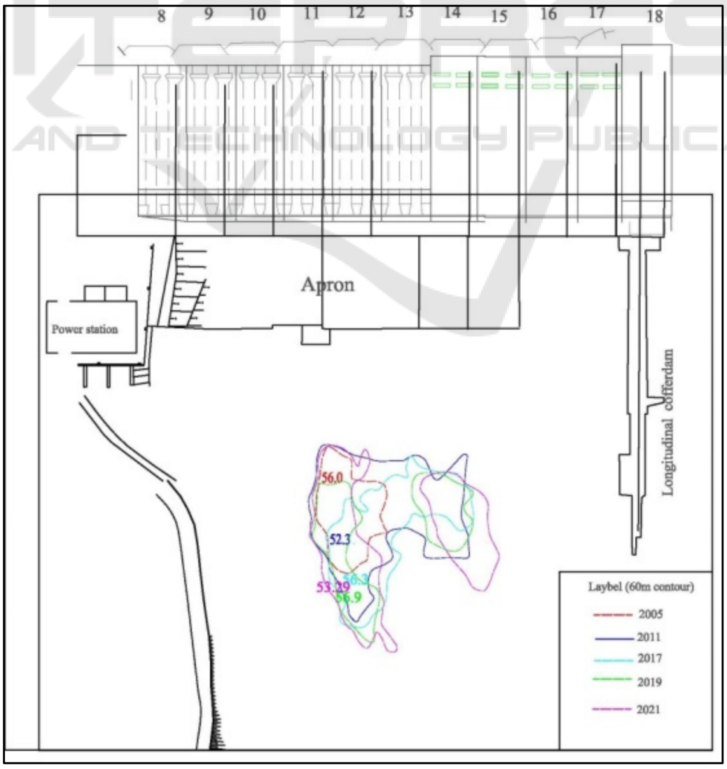

Figure 5: Horizontal changes of the scour pit in the 60m contours and the state of the lowest elevation.

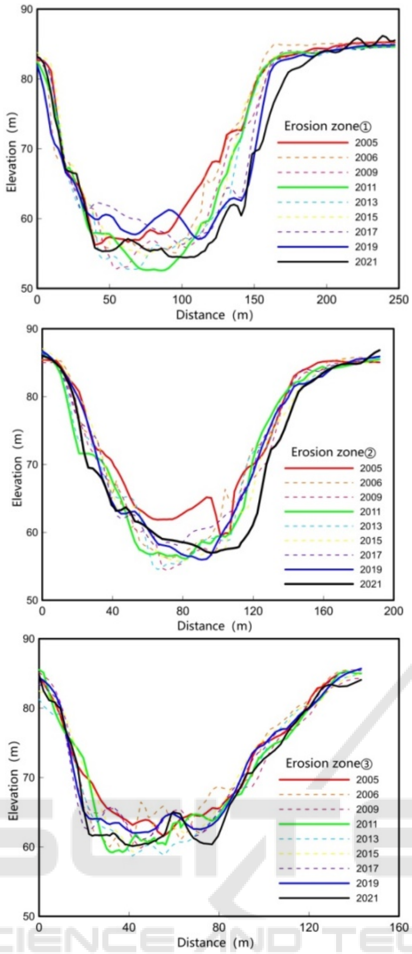

Figure 6: Changes in the profile of the erosion zone①-③.

5 EMPIRICAL ORTHOGONAL FUNCTION ANALYSIS

Based on the principle of empirical orthogonal function (EOF) analysis, this section calculate the contribution rates of different modes and corresponding spatial and temporal parameters below the 85m contour area of scour pits under the dam, so as to accurately and scientifically analyze the evolution characteristics of the scour pit under the dam. The contribution rates of the first three modes are 58.5%, 14.0% and 9.6%, respectively. Therefore, the spatial and temporal distribution characteristics of the first three modes are mainly introduced according to the proportion.

Spatial function data were processed by contour map, positive value indicated deposition(use warm colors) while negative value represents erosion(use cool colors) for making the spatial function more intuitive to show the evolution of the scour pit. As to the sedimentation area, scour is in the increasing stage of time function and sedimentation is in the decreasing stage. For the scour area, the trend is opposite.

The first mode is most considerable for morphological evolution, contributing to 58.5% of the elevation variability (fig 7a).It can be seen that the main trend of scour and accretion area of the scour pit under Danjiangkou dam: the bottom of the scour pit is gradually silted, and the slope (especially tail of the erosion zone) are gradually scoured. On the whole, the scour is the main with the maximum scour depth is 0.065m while the maximum sedimentation thickness is 0.02m. According to figure 9b, the time function corresponding to the first mode shows a rising trend, indicating that the bottom of the scour pit near the apron presents a continuous silting trend, and the tail channel of the scour zone presents a continuous scouring trend. The most intense areas of scouring and silting are located in the erosion zone①, which is consistent with the analysis results of the evolution characteristics of the scour pit in the previous chapter. Moreover, it is found that the evolution intensity is directly proportional to the gradient of time function. The change gradient of the time function from 2019 to 2021 is large, indicating that the erosion of the scour pit has the greatest impact during this period. The first mode reflects, to a certain extent, the impact of hydraulic factors (including the intensity of downstream discharge and the impact of hydraulic push caused by the water head difference and ect.) on the scouring and silting of the riverbed.

The contribution rate of the second mode is 14.0% (figure 7c), and that of the third mode is only 9.6% (figure7e). Compared with the first mode, the contribution rate of the second mode is much lower, but it can also show the evolution characteristics of the scour pit under the dam to a certain extent. The scour/silt degree of the second and third modes is relatively balanced. The scour of the second mode mainly occurs at the slope of scour pit (mainly upstream, left and right) and the bottom, and the scour range is small but the depth is large. Siltation mainly occurs downstream of the scour pit. Incorporating with the distribution of alternate time function of "W" and "M" patterns of the second mode and the evolution of scour pits over the years (figure7d), it can be seen that the second mode is an alternate scour and silting state of the scour pit, and the degree of scour and silting is basically balanced, indicating that the siltation in the downstream of scour pits is mostly from the sediment scoured down from the upstream of the scour pit.

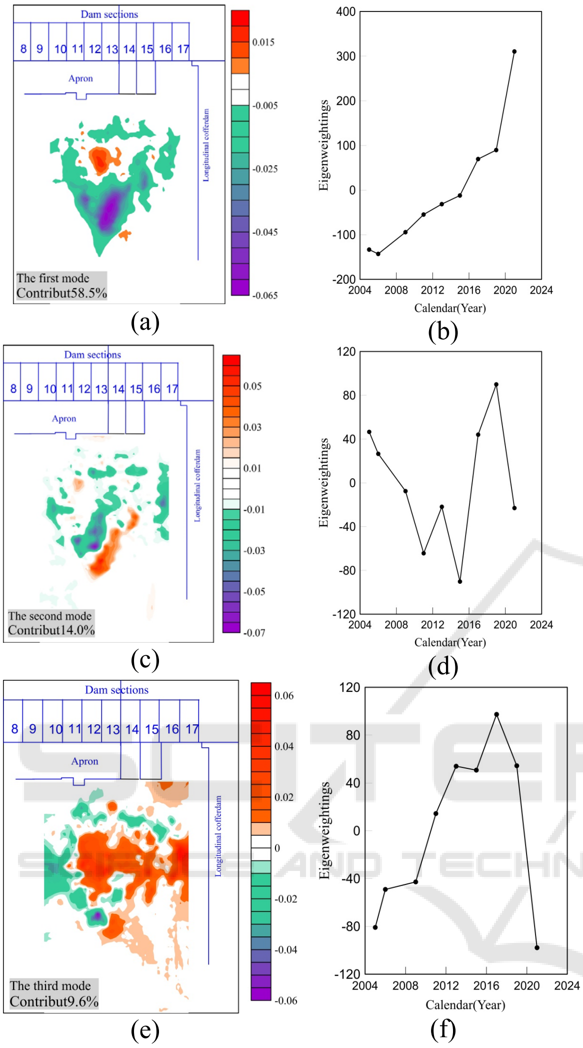

Figure 7: The time-space variation of the scour pit by the EOF analysis.

From the perspective of the spatial distribution of the third mode, the scour area mainly occurs in the slope and erosion zone①, and the siltation area is concentrated in the center and the left of the scour pit. According to the thickness distribution of scour and siltation, variations are basically the same, that is to say, the local morphological adjustment of the scour pit is mainly caused by the exchange of the center of the scour pit and the slope of the scour pit. Due to the shape of the scour pit, the sediment of the slope is prone to deposit in the middle.

6 CONCLUSIONS

During the period of 2005 to 2021, the scour pit under Danjiangkou dam was experienced significantly morphological evolution. From the horizontal plane, the scour pit gradually increased in scope, mainly reflected in the extension of the downstream area. The scour pit was mainly scoured downstream along the three erosion zones, mainly occurring in the erosion zone①. For the longitudinal perspective, the phase I (2005-2013) is the main development period of the scour pit, and the scour pit shows downward flushing depth. Scour volume in this period is 5.18×10^4 m^3 accounting for 48.1% of the total amount of scour pit, and the lowest height of scour pit decreases by about 6m.

After the implementation of the Danjiangkou dam heightening project, for the phase II (2013-2019), the scour pit developed slowly. The scour area extended downstream mainly by scouring the downstream slope. Meanwhile, the scour pit bottom showed a silting trend instead of being scoured further. The scour pit was in the redevelopment stage for the phaseⅢ(2019-2021). The scour pit was significantly deeper downstream, mainly due to the change of hydrodynamic factors, such as the significant increase of downstream discharge and the increase of water head distance. In 2021, the normal water level of the Danjiangkou dam was up to 170m the first time, and the water head difference reached 74.97m. The scour area was moved to downstream significantly. Meanwhile, the scour pit slopes (mainly the upstream near the dam apron, the right bank area and the downstream area of the erosion zone) were still be eroded.

ACKNOWLEDGMENTS

This work was supported by National Natural Science Foundation of China (Grant No. U20A20317).

REFERENCES

Akiyama, J. , Hong, L.D. , Meura, M., (2010). Analysis of scour process downstream of a sluice. *Doboku Gakkai Ronbunshuu B*, volume 35, pages 489-494.

Beckers, J.M., Rixen, M., (2003). EOF calculations and data filling from incomplete oceanographic datasets. *Journal of Atmospheric & Oceanic Technology*, volume 20(12), pages 1839-1856.

Cai. Y.J.(2007). Forecast for reservoir geological problems after dam heightening of Danjiangkou hydroprojec. *Yangtze River*.

Dai, Z., Liu, J.T, Wen, W., (2015). Morphological evolution of the South Passage in the Changjiang (Yangtze River) estuary, China. *Quaternary International*, 380-381: 314-326.

Duan, W., Zhang, H., Hou, D., (2007). Hydraulic problems caused by heightening of Danjiangkou Dam. *Hubei Water Power* .

Fan, A.M. (2021). Three-dimensional numerical simulation of local scour pit downstream of spillway sluice. *Engineering and Technological Research*.

Hamidifar, H., Omid, M.H., (2017). Local scour of cohesive beds downstream of a rigid apron. *Canadian Journal of Civil Engineering*, 44(11).

Horrillo-Caraballo, J.M, Reeve, D.E., Li, B., (2002). Eigenfunction analysis of complex estuary morphology. *Hydroinformatics 2002 Vol.1: Model Development and Data Management*. Division of Environmental Fluid Mechanics, School of Civil Engineering, University of Nottingham, University Park, Nottingham, NG7 2RD.

Hao, M., Li G.D. (2019). Erosion test on riverbed downstream spillway dam of Chaiping Hydropower Station. *South-to-North Water Transfers and Water Science & Technology* .

Hu, B., Yang, Z., Wang, H., Sun, X., Bi, N., Li,G., (2009). Sedimentation in the three gorges dam and the future trend of changjiang (yangtze river) sediment flux to the sea. *Hydrology and Earth System Sciences*, 13(11).

Li, Y.T., Sun, Z., Deng, J.N., (2003). A Study on Riverbed Erosion Downstream from the Three Gorges Reservoir. Journal of Basic Science and Engineering .

Nitsche, F.O., Ryan, W., Carbotte, S.M., Bell, R.E., Mchugh, C., (2006). Regional patterns and local variations of sediment distribution in the Hudson River Estuary. *Estuarine and Coastal Marine Science*, 259-277.

Shang, Y.P.,(2012) Research of the theory and method of design of drop-out underflow energy dissipator. *Kunming University of Science and Technology*.

Wang, C., Chen, Z., Mao, X., (2002). Hydraulics study on heightened scheme of Danjiangkou Project. *Journal of Yangtze River Scientific Research Institute* .

Wang, Q.G., Hang, H.J., Song, B., Wang, X.B., (2007). Downriver scouring pit origin analyzed in the project of raising the Danjiangkou Dam. Water Conservancy Science and Technology and Economy .

Xia, F., Zhang, Y. Z., Wei, W.U., Sun, Y., Jianhua, M.A., Can, L.I., （2009）. Progress in applications of the eof analysis in the research of coastal geomorphology and sedimentology. *Progress in Geography*, 28(2).

Yosef, G., Alpert, P., Price, C., (2017). Using EOF analysis over a large area for assessing the climate impact of small-scale afforestation in a semiarid region. *Journal of Climatology & Applied Meteorology*, 56 (9), 2545–2559.

Yuhi, M., Dang, M.H., Umeda, S., （2005）. Comparison of accelerated erosion in riverbed and downstream coast by EOF analysis. *Journal of Coastal Research*, 65(Part 1, Sp. Iss. 65):618-623.

Zhang, H., Zhang, X., Wang, X., Wu, Q., Zhao, Y., (2008). Scouring characteristics of downstream channel after operation of Danjiangkou Reservoir. *Journal of Yangtze River Scientific Research Institute,* 25(6):19-22 .

Zou, Q, Tang L , Chen J,. (2018). Study on Calculation of Scour downstream the Dam of Bazizui Hub of Xinjiang River. *Water Resources and Hydropower Engineering*.