Correction of the Artificial Influence on Dredging Volume in the Yangtze Estuary Deep-water Channel

Meng Liu*, Hong-wei ZHANG
Shanghai Estuarine and Coastal Research Center, Key Laboratory of Estuaries & Coastal Engineering, Shanghai, 201201, China
* e-mail:645903312@qq.com

Abstract: The artificial influence on dredging volume in the Yangtze Estuary Deep-water Channel is significant and complicated. By studying the relationship between daily average dredging volume and daily average residual shallow point volume, the evaluating standard and correcting method of the artificial influence on dredging volume is successfully put forward, and the key technical gap is filled. The corrected results show that: 1) The artificial influence measures are the effective ways to adjust dredging volume, and the dredging volume per year is gradually stabilized in a region with a relatively low volume and a significantly reduced range. 2) The channel quality is different each year, the dredging volume of the channel is reduced by the artificial influence but the channel quality is also reduced. 3) Since the Yangtze estuary deep water channel was opened, the decline trend of the annual silting intensity in the Nangang-yuanyuansha channel has been significant, but the tendency variation of the annual silting intensity in the North Channel, as the main object of research and improvement on sedimentation reduction, is not declining, which is actually a little bit increasing.

1. Introduction
The 12.5m deep-water channel of the Yangtze River estuary (Fig. 1) was officially opened in 2011, and the navigating depth of the Yangtze River estuary was deepened from less than 6.0m before the project to 12.5m [1]. During the construction of the project and after the completion of the project, the problem of silting in the channel is very serious [2], and the cause of silting [3-7] is also identified as a world-class difficulty, and has not yet been broken through. From 2011 to 2017, the annual average dredging volume in the Yangtze Estuary Deep-water Channel is about 75 million cubic meters. It has shown in practice that the dredging volume in the Yangtze Estuary Deep-water Channel is not only related to the silting intensity (natural factors) of the channel, but also significantly affected by the artificial influence (unnatural factors).

The artificial influence on dredging volume in the Yangtze Estuary Deep-water Channel can be described as both passive and active aspects. The passive influence is mainly caused by two factors as follow. First, the cause of silting in the Yangtze Estuary Deep-water Channel is still unknown. The temporal and spatial distribution of the channel silting volume have not been mastered. The water depth maintenance of the channel is only carried out based on a small number of static maps, and accurate maintenance can not be achieved. Therefore, the dredging volume will deviate from the actual required maintenance volume, it will be high or low. Second, there is a contradiction between the maintenance capacity of the channel and the actual required maintenance volume. The actual required maintenance volume by the channel is an ever-changing amount, but the maintenance capacity of the channel is limited. When the actual required maintenance volume by the channel
exceeds this limitation, the under-excavation situation will inevitably occur, at this time, the maintenance quality of the waterway depth is relatively low. Due to the fact that the research on the cause of silting in the Yangtze Estuary Deep-water Channel has not yet made a substantial breakthrough, the reduction of silting has been lacking effective engineering measures. In order to minimize the dredging volume and reduce maintenance costs, the project management has been actively exploring new measures since 2014, and a number of innovative measures were gradually adopted in the water depth maintenance of the channel, such as reducing the frequency of waterway assessment, extending the binning time and increasing the overflow of dredging ships, etc., all of these initiatives are active. The artificial influence on dredging volume in the Yangtze Estuary Deep-water Channel is significant and complicated, but what is the impact? This question has not been answered for many years, and the related research is still blank in the world.

Fig.1  Layout plan of the Yangtze Estuary Deep-water Channel

The amount of silting in the Yangtze Estuary Deep-water Channel was consisted by two parts, one is the dredging volume during the two mappings period, and the other is the volume of scouring or silting change between the two maps. The statistical results of annual silting and dredging volume after the official opening of the Yangtze Estuary Deep-water Channel is taken as an example (Table 1). The annual silting volume is mainly determined by the dredging volume during the two mappings (full mapping at the end of December of neighboring two years) period, and the volume of scouring or silting in the two maps was very small. It can be deduced that the annual silting volume of the Yangtze Estuary Deep-water Channel is mainly the cumulative result of the dredging volume in the routine maintenance of the channel. Therefore, the dredging volume in the Yangtze Estuary Deep-water Channel is affected by artificial influence, which in turn affects the statistical results of the volume of silting in the channel.

Table 1  Annual silting and dredging volume of the Yangtze Estuary Deep-water Channel

| year | Annual silting volume (million cubic meters) | Annual dredging volume (million cubic meters) | The volume of scouring and silting in the two maps ( million cubic meters) | The ratio of volume of scouring and silting in the two maps to annual dredging volume |
|------|---------------------------------------------|-----------------------------------------------|------------------------------------------------------------------|---------------------------------------------------------------------------------|
| 2011 | 79.56                                       | 79.35                                         | 21                                                               | 0.3%                                                                            |
| 2012 | 104.35                                      | 97.58                                         | 677                                                              | 6.5%                                                                            |
| 2013 | 81.93                                       | 86.32                                         | -439                                                             | -5.4%                                                                           |
| 2014 | 76.71                                       | 74.22                                         | 249                                                              | 3.2%                                                                            |
| 2015 | 66.02                                       | 67.93                                         | -191                                                             | -2.9%                                                                           |
| 2016 | 56.49                                       | 58.26                                         | -176                                                             | -3.1%                                                                           |
| 2017 | 51.40                                       | 58.66                                         | -726                                                             | -14.1%                                                                          |
| average | 73.78                                      | 74.62                                         | -84                                                              | -1.1%                                                                           |

Note: Negative numbers represent scouring.
The study on the cause of silting in the Yangtze Estuary Deep-water Channel requires a silting volume that can reflect the law of natural variation. However, due to the significant and complicated artificial influence, the statistical results of the silting volume on the site are increasingly unable to reflect the natural changes. This brings greater and even more insurmountable obstacles for related research work. In recent years, a variety of innovative measures have been adopted in the water depth maintenance of the channel, but the effects of these innovative measures cannot be answered, and the further optimization lacks a basis.

For scientific research and management of the Yangtze Estuary Deep-water Channel, it is important and urgent to carry out research on the artificial influence on dredging volume, explore a set of reasonable evaluation criteria and methods, realize reasonable correction of the artificial influence, and reveal the natural variation law of dredging volume.

2. Data and methods

The Yangtze Estuary Deep-water Channel is 90 kilometres long, with the E unit (Fig. 1) as the natural boundary point (Fig. 2). There are significant differences, on both sides of the channel, in the composition of silting, change law of silting volume and degree of artificial influence on dredging volume. Therefore, the Yangtze Estuary Deep-water Channel is divided into two parts for research. The E~III-I unit is the North Channel; the III-A~D unit is the Nangang-yuanyuansha channel.

![Channel unit](image)

Fig.2 Distribution of annual silting volume in the Yangtze Estuary Deep-water Channel

The water depth data and dredging volume data used for calculation are derived from engineering practice, among them, the water depth measurement of the channel utilizes a dual-frequency sounder. The data time span is from 2011 to 2017.

The residual shallow point volume described in this paper refers to the volume of earthwork in the channel that is shallower than 12.5 m. The reason why the residual shallow point volume is called is that it does not contain the volume of earthwork that has been dredged. The residual shallow point volume is obtained according to the low-frequency water depth value rather than the high-frequency water depth value. There are three main reasons: First, the stability of the low-frequency water depth measurement standard is much higher, and the reliability is better. Second, the residual shallow point volume obtained from the low-frequency depth value can be approximated as the volume of the new silt, and the dredging volume is actually calculated according to the density of the new silt, so it can be seen that the density of the two is more consistent, in comparison and the physical meaning is clear. The third is that the change process of the residual shallow point volume according to the low-frequency water depth value can better represent the change process of all the residual shallow point volume (including the high and low frequency difference parts, all calculated according to the density of new silt). In fact, even if the stability of the high-frequency water depth measurement standard is good, it is not appropriate to select the high-frequency water depth value to calculate the residual shallow point volume. It does not have the other two important characteristics of the low-frequency water depth value.
From 2011 to 2017, the variation processes of daily residual shallow point volume in the North Channel and the Nangang-yuanyuansha channel are shown in Fig.3. It can be seen that under the current conditions of water depth maintenance, the shallow points in the channel are persistent and exist every day. The role of current water depth maintenance is essential to control the shallow points in the channel to a certain extent, not to eliminate it.

Fig.3 Change process of the daily residual shallow point volume (2011~2017)

The calculation period of daily average residual shallow point volume and daily average dredging volume is the channel maintenance statistics month, and the time start and end is generally the last ten days of the adjacent two months, not according to the natural month.

3. Evaluating standard of the artificial influence on dredging volume
Take the North Channel as an example. From 2011 to 2017, the relationship between daily average dredging volume and daily average residual shallow point volume is shown in Fig.4.

It can be seen from Fig. 4 that the relationship between daily average dredging volume and daily average residual shallow point volume is relatively scattered. For example, corresponded to the same daily average residual shallow point volume, the daily average dredging volume changes very much, which in fact confirms that the artificial influence on dredging volume is very significant. If precise maintenance of the navigation channel can be achieved according to a uniform standard, then, for the same daily average residual shallow point volume, the daily average dredging volume should be very close or even equal.

All the data in Fig. 4 are grouped at equal intervals (50,000 cubic meters) by horizontal coordinates, and the vertical and horizontal coordinates average of each group data are obtained. The relationship between the daily average dredging volume and the daily average residual shallow point volume obtained from these average values is shown in Fig.5.

Fig.4 The relationship between the daily average dredging volume and the residual shallow point volume
It can be seen from Fig. 5 that there is a good power function relationship between the daily average dredging volume and the daily average residual shallow point volume in the North Channel.

Why the power function relationship between daily average dredging volume and daily average residual shallow point volume is not determined directly according to Fig. 4, this is because the data are too unevenly distributed along the horizontal coordinates, the data in the low value zone are too much. The power function based on these data is not ideal in the high value zone, and Fig. 5 can solve this problem better.

In this paper, the ratio of daily average dredging volume to daily average residual shallow point volume is defined as the maintenance coefficient, and its value reflects the quality of water depth maintenance and is dimensionless. The maintenance coefficient curve in Fig. 5 is calculated according to the power function curve, reflecting the general change law of the maintenance coefficient of the North Channel.

Along with the increase of the daily average residual shallow point volume, the maintenance coefficient of the North Channel decreases continuously, and the decrease rate is gradually slowed down. When the daily average residual shallow point volume is small to a certain level (about 100,000 cubic meters), the maintenance coefficient of the channel changes greatly, but when the daily average residual shallow point volume is large, the maintenance coefficient changes little. Except for the daily average residual shallow point volume is particularly small, the maintenance coefficient is generally less than 1. It means that the daily average dredging volume is less than the daily average residual shallow point volume under normal channel maintenance conditions, which is also an important feature of water depth maintenance in the North Channel. In addition, it clearly shows that the daily maintenance of the North Channel is significantly different from the standard of "when silted, dig it up immediately". If the standard of "when silted, dig it up immediately" can be realized in practice, the maintenance coefficient of the North Channel should theoretically tend to be infinity, and the dredging volume must increase several times more than the current situation. The practice of water depth maintenance in the North Channel clearly shows that "when silted, dig it up immediately" is unnecessary and impossible to achieve, at least under current conditions.

As the power function curve in Fig. 5 is based on the measured data of the North Channel for many years (2011-2017), it can reflect the general law between daily average dredging volume and daily average residual shallow point volume of the North Channel in these years, so this curve can be used as an evaluating standard of the artificial influence on dredging volume in the North Channel. Selecting this evaluating standard has the following three advantages:

(1) The practice significance is obvious, not imaginary.
(2) The physical concept is clear, which reflects the general law between daily average dredging volume and daily average residual shallow point volume.
(3) The standard is moderate, different standards corresponding to different dredging volume. This standard reflects the current level of channel maintenance.

4. Correcting method of the artificial influence on dredging volume

For any data of the daily average residual shallow point volume, if the corresponding daily average dredging volume is corrected according to the above evaluating standard, the daily average residual shallow point volume will also change accordingly. For example, increasing the daily average dredging volume, it will inevitably lead to the reduction of the daily average residual shallow point volume, and the reduction of the daily average dredging volume will inevitably lead to an increase in the daily average residual shallow point volume. Therefore, it is reasonable to correct the two variables of daily average dredging volume and daily average residual shallow point volume at the same time. The specific method is shown in Fig.6.

![Fig.6 The correction method of daily average dredging volume and daily average residual shallow point volume](image)

For any set of data \((v_{wh}, v_{yq})\), it must intersect with the power function curve in the vertical and horizontal directions, and the corrected result must be on the curve between the two intersection points. Because it is unknown that the exact relationship between daily average dredging volume and daily average residual shallow point volume at present, so the exact solution still cannot be achieved. However, the relationship between the two can be treated in a limited range according to the most common practice, that is, linear relations, so as to obtain an approximate solution.

The linear relationship is as follows:

\[
v_{wh} = \frac{v_{wh}}{2.3v_{yq}^{0.59}} \left( v_{yq} - v_{yq}^{0.59} \right) + v_{wh} \tag{1}
\]

The power function relationship between daily average dredging volume and daily average residual shallow point volume in the North Channel is as follows:

\[
v_{wh} = 2.3v_{yq}^{0.59} \tag{2}
\]

Among them, \(v_{wh}\) is the daily average dredging volume during two adjacent measurements of channel water depth, with unit: 10,000 cubic meters; \(v_{yq}\) is the daily average residual shallow point volume during two adjacent measurements of channel water depth, with unit: 10,000 cubic meters.

Based on formula (1) and formula (2), the artificial influence on dredging volume can be corrected.
In the same way, the correction formula for the artificial influence on dredging volume in the Nangang-yuanyuansha channel is as follows:

\[
\begin{align*}
 v_{\text{wh}} &= v_{\text{whu}} - 2.79v_{\text{vq}}^{0.34}\left(v_{\text{vq}} - v_{\text{vq'}}\right) + v_{\text{whu}} \\
 v_{\text{vq}} &= \left(\frac{v_{\text{wh}}}{2.79}\right)^{0.34} \\
 v_{\text{wh}} &= 2.79v_{\text{vq}}^{0.34}
\end{align*}
\]  

(3)

(4)

5. Corrected results of the artificial influence on dredging volume

5.1. Corrected results of the artificial influence on dredging volume in the North Channel

The corrected results of the artificial influence on dredging volume in the North Channel are shown in Fig. 7 and Fig. 8. Fig. 7 is the change process comparison before and after the correction of daily average dredging volume of the North Channel. Fig. 8 is the change process comparison before and after the correction of the annual dredging volume of the North Channel.

![Fig. 7 The change process comparison before and after the correction of daily average dredging volume of the North Channel](image)

![Fig. 8 The change process comparison before and after the correction of the annual dredging volume of the North Channel](image)
and 2015 are the silting peak years, and 2011 is the silting weakest year since the deep-water channel was officially opened.

Since 2014, a variety of active artificial measures affecting the dredging volume have been gradually taken in the water depth maintenance of the North Channel, and the artificial influence on the dredging volume has gradually increased. Before 2014, the dredging volume of the North Channel fluctuated significantly. From 2011 to 2013, the annual dredging volume was 47.97 million cubic meters, 76.59 million cubic meters and 62.88 million cubic meters, respectively (before the correction), and the fluctuation range was as high as 28.62 million cubic meters, the mean square error was as high as 11.7 million cubic meters.

After 2014, the fluctuation range for the dredging volume of the North Channel was significantly smaller. From 2011 to 2013, the annual dredging volume was 63.82 million cubic meters, 60.67 million cubic meters, 52.75 million cubic meters and 52.89 million cubic meters respectively (before the correction), and the fluctuation range was reduced to 11.07 million cubic meters, the mean square error was only about 4.84 million cubic meters. It can be inferred that the artificial factor has played a significant role in reducing fluctuations and stabilizing the dredging volume.

Compared to 2011-2013, the average annual dredging volume from 2014 to 2017 decreased significantly, from 62.47 million cubic meters to 57.53 million cubic meters, and the average annual dredging volume decreased by approximately 4.94 million cubic meters. Compared with the corrected results of the dredging volume from 2014 to 2017, the average annual dredging volume from 2014 to 2017 decreased significantly, from 62.25 million cubic meters to 57.53 million cubic meters, and the average annual dredging volume decreased by approximately 4.72 million cubic meters. It can be inferred that both compared with the previous period and compared with the corrected results of the same period, the role of artificial factors in reducing the dredging volume is much obvious.

It can be concluded from the above analysis that relying on active artificial measures, the annual dredging volume of the North Channel is gradually stabilized in a range with relatively low values and significantly reduced variation. Hence, these measures are very favourable to the target management of the dredging volume, and have become a powerful handle to regulate the dredging volume and achieve the goal management.

As mentioned above, the shallow points in the channel are persistent, so the effect of the current water depth maintenance is controlling the shallow points in the channel to a certain extent. Based on the current understanding of the law of channel silting and the current level of channel maintenance technology, the shallow point control is far from standardization and precision, which will inevitably lead to variations in the quality of channel maintenance. The corrected result of the channel dredging volume is in fact an ideal result of a standard and precise control to the shallow points, that is, the quality of the channel maintenance tends to be consistent. Therefore, it is possible to use the ratio of the annual dredging volume to its corrected result to reflect the relative quality of the annual maintenance quality of the channel. The larger the value is, the higher the annual maintenance quality is, and the smaller the value is, the lower the annual maintenance quality is. Here, the ratio is defined as the annual maintenance coefficient of the channel, dimensionless.

From 2011 to 2017, the annual maintenance coefficients of the North Channel are summarized in Table 2.

| Table 2 Annual maintenance coefficients of the North Channel |
|-------------------|--------|--------|--------|--------|--------|--------|--------|
| Year     | 2011  | 2012  | 2013  | 2014  | 2015  | 2016  | 2017  |
| Annual maintenance coefficients | 1.21  | 1.03  | 0.96  | 1.09  | 0.81  | 0.81  | 1.04  |

It can be seen from Table 2 that, as mentioned above, the annual maintenance quality of the channel is different. In contrast, the annual maintenance quality in 2011 was the highest, and its annual maintenance coefficient was as high as 1.21; the annual maintenance quality in 2015 and 2016 was the lowest, and the annual maintenance coefficients were all 0.81.

In addition, according to the annual maintenance coefficient of the North Channel, the average value from 2011 to 2013 is 1.07, and the average value from 2014 to 2017 is 0.95. It can be concluded
that the artificial influence reduces the dredging volume of the North Channel and also reduces its maintenance quality.

5.2. Corrected results for the artificial influence on dredging volume in the Nangang-yuanyuansha channel

The corrected results of the artificial influence on dredging volume in the Nangang-yuanyuansha channel are shown in Fig. 9 and Fig. 10. Fig. 9 is the change process comparison before and after the correction of daily average dredging volume of the Nangang-yuanyuansha channel. Fig. 10 is the change process comparison before and after the correction of the annual dredging volume of the Nangang-yuanyuansha channel.

![Fig.9 The change process comparison before and after the correction of daily average dredging volume of the Nangang-yuanyuansha channel](image)

![Fig.10 The change process comparison before and after the correction of the annual dredging volume of the Nangang-yuanyuansha channel](image)

Compared with the corrected results of the dredging volume from 2014 to 2017, the average annual dredging volume during this period decreased significantly, from 9.86 million cubic meters to 7.23 million cubic meters, and the average annual dredging volume decreased by 25.3%. The artificial influence plays a significant role in reducing the dredging volume of the Nangang-yuanyuansha channel. From 2011 to 2017, the annual maintenance coefficients of the Nangang-yuanyuansha channel are summarized in Table 3.

| Year | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 |
|------|------|------|------|------|------|------|------|
| Annual maintenance coefficients | 1.28 | 1.05 | 0.99 | 0.88 | 0.70 | 0.59 | 0.81 |

It can be seen from Table 3 that the annual maintenance quality of the Nangang-yuanyuansha channel is also changing. In contrast, the annual maintenance quality in 2011 was the highest, and its
annual maintenance coefficient was as high as 1.28; the annual maintenance quality in 2016 was the lowest, and the annual maintenance coefficients was only 0.59. The average annual maintenance coefficient from 2011 to 2013 is 1.11, and the average value from 2014 to 2017 is 0.75. It can be seen that the artificial influence reduces the dredging volume of the Nangang-yuanyuansha channel and also reduces its maintenance quality, which is more significant than that of the North Channel.

Different from the slight increase in natural change trends of the dredging volume in the North Channel where average annual increase is about 720,000 cubic meters, less than 1% of multi-year average (Fig.8), the natural change trend of the dredging volume of the Nangang-yuanyuansha channel is significantly reduced, with an average annual reduction of approximately 3.1 million cubic meters, more than 20% of the multi-year average.

It can be judged from the natural changes in the dredging volume on both sides of the channel that, since the Yangtze estuary deep water channel was opened the decline trend of the annual silting intensity in the Nangang-yuanyuansha channel is significant, but this trend change of the annual silting intensity in the North Channel, as the object of research and improvement on sedimentation reduction, is not declining, actually increasing a little bit more.

6. Conclusion

Under the current technical conditions, it is unrealistic to directly study the specific effects of various artificial factors, and the practical results have proved it. In another way, by studying the relationship between the daily average dredging volume and the daily average residual shallow point volume, this paper puts forward the evaluating standard and correcting method of the artificial influence on dredging volume successfully, which better solves the key technical problems of correcting the artificial influence on the channel dredging volume, thus the technical blank is filled. By correcting, the artificial influence on channel dredging volume is better filtered, the dredging volume change process after correcting can be well corresponding with the natural change trend of the channel silting intensity.

The artificial influence on dredging volume in the Yangtze Estuary Deep-water Channel is mainly manifested as both passive and active aspects, in which the active artificial influence is a powerful tool to regulate the dredging volume and achieve the goal management. Relying on the action of active artificial influence, the annual dredging volume of the channel is gradually stabilized in a range with relatively low values and significantly reduced variation.

Regardless of the North Channel or the Nangang-yuanyuansha channel, the annual maintenance quality is changed. The artificial influence reduces the dredging volume of the channel and also reduces its maintenance quality, in contrast, the Nangang-yuanyuansha channel is generally more significant than the North Channel.

Since the Yangtze estuary deep water channel was opened, the decline trend of the annual silting intensity in the Nangang-yuanyuansha channel is significant, but the trend change of the annual silting intensity in the North Channel, as the object of research and improvement on sedimentation reduction, is not declining, actually increasing a little bit more.

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