Assessment of bridge scour in the lower, middle, and upper Yangtze River estuary with riverbed sonar profiling techniques

Shuwei Zheng · Y. Jun Xu · Heqin Cheng · Bo Wang · Xuejun Lu

Received: 31 May 2017 / Accepted: 5 December 2017
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Abstract Riverbed scour of bridge piers can cause rapid loss in foundation strength, leading to sudden bridge collapse. This study used multi-beam echo sounders (Seabat 7125) to map riverbed surrounding the foundations of four major bridges in the lower, middle, and upper reaches of the 700-km Yangtze River Estuary (YRE) during June 2015 and September 2016. The high-resolution data were utilized to analyze the morphology of the bridge scour and the deformation of the wide-area riverbed (i.e., 5–18 km long and 1.3–8.3 km wide). In addition, previous bathymetric measurements collected in 1998, 2009, and 2013 were used to determine riverbed erosion and deposition at the bridge reaches. Our study shows that the scour depth surrounding the bridge foundations progressed up to 4.4–19.0 m in the YRE. Over the past 5–15 years, the total channel erosion in some river reaches was up to 15–17 m, possessing a threat to the bridge safety in the YRE. Tide cycles seemed to have resulted in significant variation in the scour morphology in the lower and middle YRE. In the lower YRE, the riverbed morphology displayed one long erosional ditch on both sides of the bridge foundations and a long-strip siltation area distributed upstream and downstream of the bridge foundations; in the middle YRE, the riverbed morphology only showed erosional morphology surrounding the bridge foundations. Large dunes caused deep cuts and steeper contours in the bridge scour. Furthermore, this study demonstrates that the high-resolution grid model formed by point cloud data of multi-beam echo sounders can clearly display the morphology of the bridge scour in terms of wide areas and that the sonar technique is a very useful tool in the assessment of bridge scours.

Keywords Bridge scour · Riverbed erosion · Channel morphology · Bridge foundation · Multi-beam echo sounders · The Yangtze River Estuary

Introduction

Riverbed scour surrounding bridge foundations is the primary cause of bridge failures. The downflow and horseshoe vortex systems are two main reasons leading to the development of bridge foundation scours (Unger and Hager 2006). A number of other factors can also play a role in bridge scour, including suspended sediment concentration (SSC) (Sheppard et al. 2004), flow depth and velocity (Melville 1992), bed material (Ataie-Ashtiani and Beheshti 2006), bridge foundation types and diameter (Melville 1992, Khosronejad et al. 2012), angle of the attack (Chang et al. 2011), channel geometry (Cardoso and Bettess 1999, Johnson et al. 2015), and bedforms (Noormets et al. 2006). Since scour depth...
and morphology are important to bridge safety, many physical and numeric modeling studies have been conducted over the past several decades to predict bridge scour (Deng and Cai 2009, Hosseini and Amini 2015).

Scour surrounding bridge foundations in unidirectional flow has been intensively investigated (Melville and Raudkivi 1977, Sheppard et al. 2004). However, the effect of bidirectional flow in tidal channels on bridge foundations is relatively little studied. Fluctuations in flow and water depth in a river channel affected by tidal cycle are more complex, which may lead to significant differences in the pattern of scouring. In a three-dimensional numeric modeling study on scour development in a three-pile group, Vasquez and Walsh (2009) found that the scour depth around the piers decreased under tidal conditions with flow reversal. Based on several previous datasets, Zanke et al. (2011) developed a universal formula for the estimation of equilibrium scour depth around a single cylindrical pile under the action of steady currents, tidal and short waves. In a flume experimental study on scour development around a vertical cylinder acting as an offshore wind turbine monopole, McGovern et al. (2014) found a symmetrical shape of a scour hole after two half-tidal cycles and that the scour hole was both more shallowly and slower-developing than the scour hole in a unidirectional current test carried out in the same flume. These studies have advanced our understanding of the foundation scour process in tidal channels. However, they are mainly laboratory experiments and the prediction equations developed are little useful for field monitoring and assessment. This is especially the case for on-site bridge scour assessment in a large river estuary with high sediment load.

The Yangtze River Estuary (YRE) is one of the most developed and the most densely populated areas in China (Gu et al. 2011). The estuary is China’s most important waterway for good transport from inland to the sea and is also one of the largest ports in the world. Understanding the change mechanism of bridge foundation scour and nearby channel morphology in the estuary is of great importance to transport and navigation safety and long-term channel stability. A few studies have been recently conducted on bridge structural health monitoring or symmetrical shape of the bridge score in the YRE (Lu et al. 2016, Wang et al. 2014). However, multi-beam echo sounders used as a tool in the assessment of bridge scour morphology influenced by different tide processes in an estuary are rare.

This study aimed to utilize the state-of-the-art multi-beam riverbed scanning techniques to investigate bridge foundation scours in a large estuarine river. Specifically, the study was aimed to (1) assess the current situation of the bridge scour in the Yangtze River Estuary, (2) investigate the characterization of scour surrounding similar bridge foundations influenced by tides in this large estuary, and (3) discern the possible factors affecting scour morphology changes in the Yangtze River Estuary.

Methods

Study area

The Yangtze River (or Changjiang in Chinese) is the third longest river in the world with a drainage area of 1.81 million km² (Cui et al. 2013, Yang et al. 2015). The upper 4300-km reach from the headwater area to Yichang is commonly considered as the upper Yangtze River (YR), and the following 950-km reach from Yichang to Hukou is considered as the middle YR, while the last 930-km reach from Hukou to the river mouth is termed as the lower YR. Normally, the last 650-km reach within the lower YR from Datong to the river mouth is named as the Yangtze River Estuary (YRE) because of the influence of tides from the East China Sea (Fig. 1). The YR delivers a large quantity of sediment to the estuary, forming many channel bars in the YRE (Gao et al. 2013, Zheng et al. 2016b). Some of these bars have formed into large islands (Fig. 1). During the past 2000 years, the lowest section of the YRE has developed three-level bifurcation and four outlets into the sea (Chen et al. 1979). Due to river engineering in the past several decades, SSC in the river has declined largely (Dai et al. 2016). The change has a significant influence on the channel stability, dune and bar development, and estuary delta evolution (Dai et al. 2016, Zheng et al. 2016a, Deng et al. 2017).

The surrounding land area of the YRE is one of the most densely populated and highly developed industrial areas in China. The region includes the Yangtze River Delta (YRD), which has approximately 11% of China’s total population and contributes to 22% of China’s total GDP (Zhang et al. 2014). Since the 1960s, many large river bridges have been built across the YRE and these bridges are important transportation links in the region.
Basic information on the study bridges

In this study, we selected four major bridges from the lower YRE to the upper YRE to assess the current scour status of bridge foundations. They include the Shanghai Yangtze River Bridge (YRB) in the lower YRE, the Second Nanjing YRB and the Dashengguan YRB in the middle YRE, and the Tongling YRB in the upper YRE. Table 1 provides some basic information on the bridge foundations and river flow conditions.

Data collection

In this study, we created digital elevation model (DEM) datasets to assess morphological changes over time. Specifically, the north channel bathymetric data for 2009 and 2013 were used to analyze the morphological variation near the Shanghai YRB in the lower YRE. These data were surveyed by the Navigation Guarantee Department of the Chinese Navy Headquarters (NGDCNH) and the Maritime Safety Administration of People’s Republic of China (MSAPRC), respectively. In addition, the navigation maps from Tongling to Nanjing for 1998 and 2013 created by the Chang Jiang Waterway Bureau (CJWB) were also collected to analyze the morphological change near the Second Nanjing YRB and the Dashengguan YRB in the middle YRE and the Tongling YRB in the upper YRE (Table 2).

Bridge scour measurements

We used a multi-beam echo sounder (MBES; Teledyne RESON, SeaBat 7125) to survey the riverbed of the four studied river reaches. A boat mounting the sounder traveled the reaches several times during June 2015 and September 2016. The sounder has an operational working frequency of 200/400 kHz. The theoretical depth resolution is 6 mm, and typical depth measurements are 0.5 to 150 m at 400 kHz and 0.5 to 400 m at 200 kHz. The along-track transmitted beam widths are
2° at 200 kHz and 1° at 400 kHz, and the across-track received beam widths are 1° at 200 kHz and 0.5° at 400 kHz. It has 512 beams at 400 kHz. This equipment has a maximum swath angle of 140° in equal-distance mode and 165° in equal-angle mode. During the surveying, a Trimble real-time differential global positioning system (DGPS) was used to control the position accuracy at the decimeter level. The speed of the measuring boat was controlled at 1–3.5 m/s, and the threshold of maximum ping rate was 20 Hz which can automatically adjust with water depth. The equal-distant mode and a swath angle of 140° were chosen in acquisition module of the PDS 2000 control center. A flat seafloor with a slope in the downstream of the Shanghai YRB and in the Nanjing reach of the YR was chosen for multi-beam calibration of roll, yaw, and pitch, respectively. The final data were also corrected for sound speed and abnormal beams. Four piers were selected to study the morphological characters and maximum scour depths in the YRE.

Estimation of erosion and deposition rates

The Chinese National Grid coordinates was used to geo-reference all collected bathymetric charts with nine benchmarks in ArcGIS 10.4. Isobaths of water depths 0, −2, −5, and −10 m in the river channel were transformed into elevation points with a spacing of 50–80 m between two adjacent points on the isobaths. Points of water depth were also transformed into elevation. These point cloud data were relative to Beijing 1954 coordinates. Subsequently, the Kriging technique was utilized to interpolate the digitized data into grid with 100 × 100 m resolution. Deposition or erosion of the channel was estimated by subtracting the grid file of 1 year from that of another. An 18-km long river reach was chosen to estimate the deposition and erosion rates near the Shanghai YRB between 2009 and 2013. A 7.0-, 9.0-, and 5.0-km long river reaches were chosen to estimate the deposition and erosion rates near the Second Nanjing YRB, the Dashengguan YRB, and the Tongling YRB between 1998 and 2013, respectively. The errors of the Kriging were related to the accuracy of the collected depth data from the maps and the riverbed morphology (e.g., slope). Previous studies have analyzed some of the river segments of the lower Yangtze River and have reported a low gradient of the riverbed (Wang et al. 2009; Luo et al. 2017). Especially, for the reaches of the Tongling YRB, Second Nanjing YRB, Dashengguan YRB, and Shanghai YRB, the river gradient was estimated to be 1‰–1% (Chen et al. 2012). Luo et al. (2017) postulated that in using the Kriging interpolation technique for such low-gradient riverbeds, errors could be assumed to be low (<

<table>
<thead>
<tr>
<th>Name</th>
<th>Built</th>
<th>Foundation type</th>
<th>Foundation dimension (m)</th>
<th>Riverbed conditions</th>
<th>Flow depth (m)</th>
<th>Mean velocity (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>2009</td>
<td>Rectangular pile cap with a round head</td>
<td>37.2 × 72.2</td>
<td>Plane bed</td>
<td>16.3</td>
<td>–</td>
</tr>
<tr>
<td>B</td>
<td>2001</td>
<td>Cylindrical cofferdam</td>
<td>38.2 × 80.2</td>
<td>VLD5</td>
<td>32.3</td>
<td>1.23</td>
</tr>
<tr>
<td>C</td>
<td>2011</td>
<td>Rectangular cofferdam with round head</td>
<td>36 × 36</td>
<td>SD5</td>
<td>15.2</td>
<td>1.21</td>
</tr>
<tr>
<td>D</td>
<td>1991</td>
<td>Cylindrical cofferdam</td>
<td>31 × 31</td>
<td>SD5</td>
<td>25.7</td>
<td>1.32</td>
</tr>
</tbody>
</table>

Table 2  Navigation charts used for creating the digital bathymetric data of the Yangtze River Estuary, China

<table>
<thead>
<tr>
<th>Year</th>
<th>Map title</th>
<th>Scale</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>1998</td>
<td>Baguazhou waterway</td>
<td>1:40,000</td>
<td>CJWB</td>
</tr>
<tr>
<td>1988</td>
<td>Jiangxinzhou to Xinjizhou</td>
<td>1:40,000</td>
<td>CJWB</td>
</tr>
<tr>
<td>1998</td>
<td>Henggang to Chongwenzhou tail</td>
<td>1:40,000</td>
<td>CJWB</td>
</tr>
<tr>
<td>2009</td>
<td>Southern part of Changjiang Kou</td>
<td>1:130,000</td>
<td>NGDCNH</td>
</tr>
<tr>
<td>2013</td>
<td>Qixiashan to Zhongshan Harbor</td>
<td>1:40,000</td>
<td>CJWB</td>
</tr>
<tr>
<td>2013</td>
<td>Zhongshan Harbor to Quingzhou</td>
<td>1:40,000</td>
<td>CJWB</td>
</tr>
<tr>
<td>2013</td>
<td>Zhangjiangzhou to Hejiachang</td>
<td>1:40,000</td>
<td>CJWB</td>
</tr>
<tr>
<td>2013</td>
<td>Hejiachang to Nizhou</td>
<td>1:40,000</td>
<td>CJWB</td>
</tr>
<tr>
<td>2013</td>
<td>Changjiang Kou and approaches</td>
<td>1:150,000</td>
<td>MSAPRC</td>
</tr>
</tbody>
</table>

CJWB Chang Jiang Waterway Bureau, NGDCNH Navigation Guarantee Department of the Chinese Navy Headquarters, MSAPRC Maritime Safety Administration of People’s Republic of China
10%). In our study, the volumes of erosion and deposition were calculated through the method of Wheaton et al. (2009).

Net erosion volume was calculated as follows:

\[ E_{\text{net}} = E_v - D_v \]  

where \( E_{\text{net}} \) is the net erosion volume, \( E_v \) is the erosion volume, and \( D_v \) is the deposition volume.

Average erosion depth was calculated by

\[ E_{\text{depth}} = \frac{E_{\text{net}}}{S_{\text{total}}} \]

where \( E_{\text{depth}} \) is the average riverbed erosion depth and \( S_{\text{total}} \) is the total surface area of the river reach near the Shanghai YRB in 2009 or near the other studied bridges in 1998.

Erosion rate is calculated as

\[ E_{\text{rate}} = \frac{E_{\text{depth}}}{n} \]

where the \( E_{\text{rate}} \) is the erosion rate and \( n \) is the number of years, which is 4 (2009–2013) for the Shanghai YRB and 15 (1998–2013) for the other three bridges.

Results

Channel erosion and deposition near bridges

Overall, the channel of the four studied reaches experienced erosion in different degrees over the past 5–15 years (Table 3). The Dashengguan YRB reach had the largest percentage of area eroded (94%), followed by the Tongling YRB reach (85%), the Shanghai YRB reach (80%), and the Second Nanjing YRB reach (58%). The Dashengguan YRB reach also showed the highest erosion rate (0.33 m/year), followed by the Shanghai YRB reach (0.28 m/year), the Tongling YRB reach (0.15 m/year), and the Second Nanjing YRB reach (0.03 m/year).

Scour morphology surrounding the bridge foundations

Bridge scour and riverbed morphology grid models with 1 × 1 m resolution were generated in PDS 2000 by using the raw data of point clouds. High-resolution data can display much more details of bridge scour, allowing more accurate quantification of scour depth and length (Fig. 2 and Table 4). The results showed that the scour morphology of the studied bridges in the lower, middle, and upper YRE showed different patterns. For the rectangular pile cap bridge foundations, the riverbed morphology of the Shanghai YRB in the lower YRE had a long erosional ditch distributed on both sides of the bridge foundation while two long-strip siltation areas were distributed on the upstream and downstream of the bridge foundation (Fig. 2a). However, in the middle YRE, the riverbed morphology of the Dashengguan YRB only showed erosional morphology without a siltation area surrounding the bridge foundation (Fig. 2b). Furthermore, the maximum depth of scour surrounding the Dashengguan bridge foundation was about 8.8 m, while the maximum depth of the Shanghai YRB was only half (4.4 m) (Table 4). The longitudinal scouring depths at the Shanghai YRB and the Dashengguan YRB were approximately 316 and 518 m (Table 4), respectively.

For the cylindrical cofferdam bridge foundations, the scour morphology shows a horseshoe shape in the middle and upper YRE (Fig. 2c, d). The extent of the longitudinal scouring was approximately 395 m at the Second Nanjing YRB but was only about 227 m at the

| Table 3 | Changes in channel bathymetry near the four major bridges in the lower (A), middle (B and C), and upper (D) Yangtze River Estuary, China. The letters A–D denote the river reach of the Shanghai YRB, the Second Nanjing YRB, the Dashengguan YRB, and the Tongling YRB, respectively. The erosion, deposition, and erosion/deposition ratio (E/D rate) were calculated using the 2009–2013 bathymetric survey data for the Shanghai YRB reach and the 1998–2013 bathymetric survey data for the other three YRB reaches. Erosion and deposition percentages were calculated based on the area, and positive values indicate erosion |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Erosion volume × 10^6 m^3 | Deposition volume × 10^6 m^3 | Erosion percentage | Deposition percentage | E/D rate | Width | Length |
| A | 197.6 | 50.6 | 80 | 20 | +0.28 | 8.3 | 18.0 |
| B | 13.1 | 9.5 | 58 | 42 | +0.03 | 1.3 | 7.0 |
| C | 26.2 | 6.6 | 94 | 6 | +0.33 | 1.4 | 9.0 |
| D | 17.1 | 3.1 | 85 | 15 | +0.15 | 1.3 | 5.0 |
The flood-ebb tide process can change flow conditions in terms of velocity, direction, and flow depth (Edge et al. 1998, Noormets et al. 2006). The highest tide level at Niupi Jiao (approximately 640 km downstream the Datong station) has been reported to be 4.5 m, while the highest tide at Jiangyin station (415 km downstream of Datong, Fig. 3) has been reported to be 3.1 m. However, the reaches below Jiangyin still experience the flood-ebb tide process while the upstream only has a tide level change (Fig. 3). Our study shows that the flood-ebb tide process can cause significant variation in bridge scour morphology. For example, the Shanghai YRB and the Dashengguan YRB have similar bridge foundations and flow depth (Table 1). Due to the Shanghai YRB being significantly influenced by the flood-ebb tide process, where the preferential flows of ebb tide accounted for approximately 66.5 to 79.2% (Lu et al. 2016), its bridge scour showed two long-strip siltation areas distributed on the upstream (~4.3 m) and downstream (~4.4 m) of the bridge foundations (Table 4). The Dashengguan YRB being located in the Nanjing Waterway (the highest tide level 1.2 m), 205 km upstream of Jiangyin, it is only influenced by the tide level change (Dai and Liu 2013) and the scour morphology showed no siltation area surrounding the bridge foundation.

In the flood-ebb tide-affected channels, the bridge scour showed two long-strip siltation areas distributed on the upstream and downstream of the bridge foundation (Fig. 2a). This phenomenon may have been a result of the location of the water depth of the top point in the siltation area. The values near the white dots are the average water depths of the riverbed surface which was not affected by the bridge scour. The maximum bridge scour depth was calculated as the difference between the maximum water depth and the average depth of the riverbed surface. All depth values in this figure were calculated according to the reference water levels.
of the periodic change in flow velocity and direction. A similar situation has been reported by Vasquez and Walsh (2009) who simulated a three-pile group scour under tidal flow using a three-dimensional hydrodynamic modeling. During the ebb tide, the riverbed surrounding the bridge foundation is eroded by the downflow and horseshoe vortex, while a long-strip siltation area formed downstream of the bridge due to the wake (Lu et al. 2016). Similar to that, another long-strip siltation area developed at the upstream of the bridge foundation during the flood tide (Lu et al. 2016). However, in the river reach without flood-ebb tide influence, the bridge scour morphology is different, i.e., there is no siltation area surrounding the Dashengguan YRB foundation (Fig. 2b).

The development of very large dunes can significantly change the scour morphology. A previous study has shown that dunes are of great significance to scour depth surrounding bridge foundations (Noormets et al. 2006). The Tongling YRB and Second Nanjing YRB are located in the upper and middle reaches of the YRE, which can be influenced by tide only during low-flow

![Fig. 3](image-url) Information on tide level and the maximum depth of bridge scours. The gray dashed line is the dividing line of the unidirectional flow and bidirectional flow. The river reach downstream Jiangyin has bidirectional flow influenced by flood-ebb tide process while the river reach upstream has unidirectional flow mainly influenced by river discharge. Red triangles are the maximum scour depth at the four studied bridges. Blue diamonds are the highest tide level observed at the hydrological and tide stations. Tide level data for Datong and Nanjing were collected from the hydrological stations of Datong and Nanjing (Xu et al. 2012). Tide level data downstream of Jiangyin came from several local tide stations.
periods. The bridge foundations are similar in size and type, and the scour morphology has a horseshoe pattern (Fig. 4); thus, they can be used to study how very large dunes affect the bridge scour morphology. The multibeam data in our study show that very large dunes with a wavelength greater than 122 m and a height greater than 4.9 m developed on the riverbed of the Second Nanjing YRB (Fig. 4a), indicating more complex scour morphology at the Tongling YRB (without very large dunes developing in the bridge scour). At the same time, cross-sections parallel or perpendicular to the flow also show the same results (Fig. 4).

Previous studies have reported that SSC plays a significant role on the equilibrium of scour depth. Low SSC may lead to an increase of the time and maximum scour depth around a bridge foundation (Sheppard et al., 2004). The SSC of the Yangtze River has largely declined since the late 1980s, resulting in a sharp reduction in the river’s sediment yield, especially after the completion of the Three Gorges Dam (TGD) (Fig. 5). As a highly SSC-laden river in the world, the YR used to have an average SSC of 0.62 kg/m³ between 1956 and 1970, followed by a reduced SSC (0.42 kg/m³) between 1971 and 2002 (Dai and Liu 2016). In the past decade, the river showed a sharp decline in SSC, with an average of only about 0.18 kg/m³ between 2003 and 2013 (Dai et al. 2016). It is difficult to quantify the effect of this reduction on the intensity of bridge scour and riverbed deformation. However, our results indicate that the reduced sediment load may be responsible for excessive bridge scour and riverbed erosion in the upper and middle YRE, as well as for an insufficient deposition downstream the Shanghai YRB in the relatively strongly tidal-affected channel.

The YR has distinct seasonal and secular variability in river stage and discharge (Dai and Liu 2013). During 2014 and 2016, the river stage fluctuated from 4.5 to 15.6 m, corresponding to a large flow variation from 1.0 to $6.9 \times 10^4$ m³/s at Datong (Fig. 5). Different river stage and discharge lead to the scour morphology constantly adjusting (Sheppard et al. 2004, Noormets et al. 2006). The river stage and discharge were also affected by the operation of the TGD. By the impounding and releasing of water,
the TGD increased the water discharge in the dry season and reduced the flood peak discharge (Guo et al. 2012). Therefore, the natural seasonal and internal variability of discharge and operation of TGD in the dry/flood season will continue to influence the scour morphology and scour depth in the future.

Channel erosion is a common problem in rivers that bridge foundations have to experience during their design life (Keshavarzi and Noori 2010, Johnson et al. 2015). Even though bridge foundations can lead to local riverbed erosion, which may be a threat to the bridge safety, the channel erosion in a large scale in the long run by nature and human activities also is one of the most important factors for bridge safety in the YRE. The multi-beam data showed that the scour depth surrounding the bridge foundations could progress up to 4.4–19.0 m in the studied bridges. However, the river regime and cross-sections (Fig. 6) at the upstream and downstream (100 m away from the bridge foundation) of each bridge segment showed that most of the riverbed at the main bridge foundations experienced erosion in recent years. For instance, the main channel of the Shanghai YRB segment has experienced a notable erosion from 2009 to 2013 (Fig. 6a, b), and approximately 2.0–2.5 and 2.5–3.0 m of the riverbed were scoured at the upstream and downstream of the Shanghai YRB, respectively (Fig. 7a, b). These results also occurred at the Tongling YRB segment where about a depth of 1.0–2.0 and 4.5–5.5 m of riverbed were eroded at the up- and downstreams of the bridge foundation (Figs. 6g, h and 7g, h). Although the studied bridge foundations at Dashengguan YRB (built in 2011) showed little erosion from 1998 to 2013, the riverbed surrounding the two main bridge foundations was eroded by about 15.0–17.0 m (Fig. 7e, f). It is worth noting that although the Second Nanjing YRB river segment has experienced minor erosion (0.03 m/year), the up- and downstreams of the bridge foundations were scoured by 5.5–6.0 and 3.5–4.0 m, respectively (Fig. 7c, d). Although local scour surrounding bridge foundations was part of the channel erosion, the channel erosion in a large scale can be considered as not being affected by bridge foundations. As a result, the long-time channel erosion could reach up to 15.0–17.0 m in the YRE which is also one of the most important factors for bridge safety.

Monitoring bridge scour is widely conducted by engineers to assess bridge foundation conditions. Current monitoring procedures focus on the bridge scour, lacking the ability to observe wide riverbed areas near a bridge on operational time scales. It is, however, important that wide areas are observed up- and downstream of the bridges, especially in an estuarine channel where erosional and depositional patterns in the wide areas can directly respond to the bridge foundations and their erosion. Overall, this study demonstrates that the three-dimensional sonar profiling provides high-resolution multi-beam data over a wide area, which can be very useful to assess bridge scour and riverbed deformation.
When compared with other monitoring approaches, such as using traditional sounding line or single-beam data, the multi-beam sonar profiling can efficiently provide higher resolution and more precise point data of bridge foundations and nearby areas with great scouring.
Fig. 7 Cross-sectional change of the river channels at the upstream (a) and downstream (b) of the Shanghai YRB, at the upstream (c) and downstream (d) of the Second Nanjing YRB, at the upstream (e) and downstream (f) of the Dashengguan YRB, and at the upstream (g) and downstream (f) of the Tongling YRB in the YRE. Cross-sections at the upstream or downstream of these bridges are 100 m away from the bridges.
Conclusions

This study used multi-beam echo sounders to survey the riverbed along four major bridges in the upper, middle, and lower Yangtze River Estuary during June 2015 and September 2016. The high-resolution data allowed detailed mapping of the river reaches, demonstrating the great usefulness of the techniques in assessing bridge scours and riverbed deformation patterns near the bridges. In addition, previous bathymetric measurements in 1998, 2009, and 2013 were utilized to determine longer-term riverbed erosion and deposition at the bridge reaches. This study found large scour depths at the bridge foundations up to 19 m and extensive erosion of the riverbed near the bridges up to 0.33 m/year in recent years. The flood-ebb tide seemed to have resulted in significant variation in the scour morphology in the lower and middle YRE. In the lower YRE, the scour morphology and riverbed erosion were clearly reflected by tidal influence, displaying long erosional ditches distributed on both sides of the bridge foundation and long-strip siltation areas on the upstream and downstream of the bridge foundations. In the middle of YRE, the riverbed morphology only showed erosional morphology surrounding the bridge foundations. Very large dunes can significantly change the scour morphology, leading to steeper contours of riverbed scour. Due to the operation of the Three Gorges Dam upstream of the YRE, sediment inflow into the YRE will unlikely change in the future, and insufficient sediment offsetting the channel erosion may become a serious problem for bridge safety in the YRE.

Acknowledgements During the preparation of this manuscript, Shuwei Zheng was supported by an award of the China Scholarship Council (File No. 201606140126). We would also like to thank an anonymous reviewer for reviewing the manuscript and offering many helpful suggestions, which have helped improve the quality of this paper.

Funding information This study was financially supported through a grant from the Natural Science Foundation of China (Grant No. 41476075) and a grant from the Impact of Major Projects on the geological environment of the Yangtze River (Grant No. DD20160246). The study also benefited from a US Department of Agriculture Hatch Fund project (Project No. LAB94230). The statements, findings, and conclusions are those of the authors and do not necessarily reflect the views of the funding agencies.

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