Multi-approach analysis of maximum riverbed scour depth above subway tunnel

Jun CHEN¹,², Hong-wu TANG*¹,², Zui-sen LI¹,², Wen-hong DAI¹,²

¹. State Key Laboratory of Hydrology-Water Resources and Hydraulic Engineering, Hohai University, Nanjing 210098, P. R. China
². National Engineering Research Center of Water Resources Efficient Utilization and Engineering Safety, Hohai University, Nanjing, 210098, P. R. China

Abstract: When subway tunnels are routed underneath rivers, riverbed scour may expose the structure, with potentially severe consequences. Thus, it is important to identify the maximum scour depth to ensure that the designed buried depth is adequate. There are a range of methods that may be applied to this problem, including the fluvial process analysis method, geological structure analysis method, scour formula method, scour model experiment method, and numerical simulation method. However, the application ranges and forecasting precision of these methods vary considerably. In order to quantitatively analyze the characteristics of the different methods, a subway tunnel passing underneath a river was selected, and the aforementioned five methods were used to forecast the maximum scour depth. The fluvial process analysis method was used to characterize the river regime and evolution trend, which were the baseline for examination of the scour depth of the riverbed. The results obtained from the scour model experiment and the numerical simulation methods are reliable; these two methods are suitable for application to tunnel projects passing underneath rivers. The scour formula method was less accurate than the scour model experiment method; it is suitable for application to lower risk projects such as pipelines. The results of the geological structure analysis had low precision; the method is suitable for use as a secondary method to assist other research methods. To forecast the maximum scour depth of the riverbed above the subway tunnel, a combination of methods is suggested, and the appropriate analysis method should be chosen with respect to the local conditions.

Key words: high flow; subway tunnel; scour depth; scour model; numerical simulation

1 Introduction

Subway tunnels serve a useful function in relieving transport congestion. As a result of recent rapid urban development, subway systems are being constructed across China. Tunnel engineering necessitates a high level of safety specification; if the design and construction is

This work was supported by the National Natural Science Foundation of China (Grants No. 50909037, 50879019, and 50879020), the Natural Science Foundation of Hohai University (Grant No. 2008426611), the Foundation for Introducing Talents of Hohai University (Grant No. 20080415), the National Science and Technology Pillar Program during the Eleventh Five-Year Plan Period (Grant No. 2008BAB29B08), and the Fundamental Research Funds for the Central Universities (Grant No. 2010B01114).

*Corresponding author (e-mail: hwtang@hhu.edu.cn)
Received Jul. 7, 2010; accepted Nov. 4, 2010
unsuitable, an accident could occur and cause loss of life and property. The presence of rivers is an unavoidable inconvenience in many cities where tunnels are constructed. In the event that the buried depth of a subway tunnel is insufficient, water gushing could occur in the tunnel, which could cause peripheral ground collapse. For example, on July 1, 2003, in Shanghai, inadequate construction techniques led to water gushing, which damaged the tunnel and caused ground subsidence. In the interest of the safe operation of subway tunnels passing underneath rivers, it is critical to determine the maximum scour depth of the riverbed to obtain an appropriate buried depth design.

Riverbed scour may be broadly divided into local scour and natural scour. Nowadays, there is widespread research on local scour that occurs as a result of the presence of stream structures (Koustuv and Susanta 2010; Lai et al. 2009; Lu and Cai 2010; Bolduc et al. 2008). In contrast, there is less research on the natural scour behavior of a riverbed (Saleh 1993). As the subway tunnel structure is subterranean with no protruding structure, the riverbed scour is natural. Methods used to assess the scour depth include the fluvial process analysis method (Xie et al. 2009), geological structure analysis method, and scour formula method (Dong 2009), which are used to calculate the appropriate buried depth for pipelines. Additional methods, including the scour model experiment method (Ataie-Ashtiani et al. 2010; Demir and Garcia 2007) and numerical simulation method (Liang and Cheng 2005; Zhao and Cheng 2008), are used to research the river evolution. The aforementioned five methods have different ranges of application and forecasting precision. In order to ensure the reliability of research results, it is necessary to identify the maximum scour depth of the riverbed with complementary methods. Shi et al. (2008) investigated the scour depth of a riverbed above a subway tunnel in the Qiantangjiang Estuary with methods that included fluvial process analysis, physical model experiments, and numerical simulation, obtaining a reasonable forecast result. In order to determine the application ranges and forecasting precision of different methods, this study examined the subway tunnel underneath tidal rivers in Ningbo City, and used the aforementioned five methods to forecast the maximum scour depth. In order to ensure the reliability of research results, the results obtained by different methods were compared.

2 Study area

The subway system will be constructed in Ningbo City, and parts of subway lines will pass under three rivers, including the Fenghuahe River, the Yaohe River, and the Yonghe River. The Yonghe River is formed by the confluence of the Fenghuahe and Yaohe rivers, and it flows into the East China Sea. The confluence basin is shown in Fig. 1. There is a tidal gate on the Yaohe River. Subway line 1 will pass underneath the Fenghuahe River near the Jiangxia Bridge. The subway project includes the option of a southern or northern route, located 24 m upstream or downstream of the bridge, respectively. A schematic diagram of the subway line is shown in Fig. 2. When high flows occur, the riverbed above the subway tunnel will be scoured,
which could endanger the safety of the subway tunnel. Therefore, it is crucial to determine
the maximum scour depth of the riverbed above the subway tunnel. Five methods, including
the fluvial process analysis method, geological structure analysis method, scour formula
method, scour model experiment method, and numerical simulation method were used to
forecast the maximum scour depth. The results provide guidance for safe design of the
subway tunnel.

3 Forecast of riverbed scour depth

3.1 Fluvial process analysis method

The fluvial process analysis method examines the river regime and evolution trend by
comparing historical morphological evolution data. In general, a regression formula describing
the relationship between the flow discharge, riverbed topography, and scour depth is
established according to the historical hydrologic and topographic data of the river. The
formula may then be used to obtain the maximum scour depth of the riverbed.

Due to the lack of historical hydrologic and topographic data series for the Fenghuahe
River, the scour formula cannot be established. The river regime and evolution trend can be
forecasted by analyzing the historical morphological evolution data of the Fenghuahe River.
The Fenghuahe River characteristics are as follows: the annual average runoff is $1.69 \times 10^9$ m$^3$;
the annual average flood tidal influx volume and ebb tide influx volume are $5.76 \times 10^9$ m$^3$ and
$7.4 \times 10^9$ m$^3$, respectively; the annual average sediment discharge is $4.35 \times 10^4$ t; the width of
the river ranges from 90 m to 180 m; and the average slope of the river is 0.81%. The tidal
gate on the Yaohe River, built in 1959, is located 3.5 km upstream of the river junction. The
Fenghuahe River, the Yaohe River downstream of the tidal gate, and the Yonghe River are all
tidal rivers. The embankment engineering projects of the three rivers in the city can protect
against a 100-year return period flood. The morphology of the reach from Chenglangyan to the
river junction has a low sinuosity, and the cross section of the reach maintains an almost
regular U-shape. The location of the river thalweg has apparently not shifted for several years,
so it is assumed to be stable. The fluvial process of the Fenghuahe River is shown in Fig. 3,
and it may be described as follows: Compared with the topographic contours of the riverbed in 1951, the −4 m contour line and −10 m contour line moved from the riverbank toward the river center in 2005, and the distances of the movements were 15 m and 10 m, respectively. This implies that deposition of sediment in the river occurred from 1951 to 2005. There have recently been construction projects affecting the flow movement, including bridges and wharves, which are increasing the rate of sediment deposition in the river. The riverbed of the Fenghuahe River is always in the depositing state except when high flows occur.

![Fluvial process of Fenghuahe River](image)

**Fig. 3** Fluvial process of Fenghuahe River

### 3.2 Geological structure analysis method

The river is the product of flow and riverbed interaction, so the historical evolution process is reflected in the geological layers of the riverbed. The research procedure of the geological structure analysis method of forecasting the maximum riverbed scour depth is as follows: First, the characteristics and spatial distribution of the quaternary strata of the riverbed were analyzed to describe the historical evolution process. Then, the recent flow conditions and river evolution trend were combined to forecast the maximum scour depth of the riverbed. The geological structure and the characteristics of soil layers under the riverbed of the subway tunnel in Ningbo City are shown in Table 1.

<table>
<thead>
<tr>
<th>Soil layer number</th>
<th>Components of soil layer</th>
<th>Formation of soil layer</th>
<th>Thickness (m)</th>
<th>Description of soil layer</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-2</td>
<td>Alluvial soil with round gravel</td>
<td>Hydraulic fill</td>
<td>1.0-4.3</td>
<td>Inhomogeneous compaction degree</td>
</tr>
<tr>
<td>2-2</td>
<td>Gray silty clay</td>
<td>Marine deposition</td>
<td>5.3-8.2</td>
<td>Medium toughness, medium dry strength</td>
</tr>
<tr>
<td>1</td>
<td>Dark green and yellow silty clay</td>
<td>Lacustrine deposition</td>
<td>5.5-15.0</td>
<td>High toughness, high dry strength</td>
</tr>
</tbody>
</table>

With the increase of the depth of the riverbed, the geological structure under the riverbed at the location where the subway tunnel was considered to be constructed was classified into three layers, 1-2, 2-2, and 1. Geological structure analysis shows that the riverbed evolution at the location of the subway tunnel occurred in soil layer 1-2, and that the historical maximum scour depth did not exceed 4.3 m. The thickness between the tunnel top and the riverbed must exceed 6 m; therefore, a safe subway tunnel depth would be greater than 10.3 m. This means that the subway tunnel will be located in soil layer 1.

### 3.3 Scour formula method
The scour formulas are built on the basis of observed data from the river and experimental data. The Lacey formula, scour rate formula, and scour formula of bridge crossings (Huang et al. 1998) are often used. The scour formula of bridge crossings is most often used in China.

Considering that the riverbed of the Fenghuahe River is clay, the scour formula for a clay riverbed (HPDIMC 1991) is used to calculate the maximum scour depth at the location of the subway tunnel. The formula can be expressed as

$$h_p = \frac{AQ}{\mu B} \left( \frac{h_{\max}}{h_c} \right)^{\frac{5}{3}} \frac{1}{\left( \frac{1}{I_1} \right)^{\frac{5}{3}}}$$

where $h_p$ is the water depth after scouring (m), $A$ is the concentration coefficient of unit width discharge with a value of 1.0, $Q$ is the design discharge of the main channel (m$^3$/s), $\mu$ is the compression coefficient of lateral flow with a value of 0.99, $B$ is the total width of the Jiangxia Bridge opening in the main channel (m), $h_{\max}$ and $h_c$ are the maximum and average water depths of the main channel around Jiangxia Bridge before scouring (m), respectively, and $I_1$ is the liquidity index of clay around Jiangxia Bridge with a value in the range of 0.9 to 1.10.

The embankments built around the three rivers in the city were designed to protect against a 100-year return period flood, and the freeboard height was 0.5 m. When a 200-year return period flood in the Fenghuahe River occurred, the embankment was not overtopped. The most disadvantageous hydrologic conditions would be a combination of the 200-year return period flood in the Fenghuahe River and the 5-year highest tide in the Yonghe River. Eq. (1) was used to calculate the scour depth of the riverbed above the subway tunnel under these extreme conditions. A study involving the northern route scheme was considered. The results showed that in the event of the 200-year return period flood of the Fenghuahe River, the maximum flood discharge would be 2 719.2 m$^3$/s, and the maximum water depth of the main channel around Jiangxia Bridge before scouring would be 9.28 m. The water depth after scouring would be 12.67 m, and the maximum scour depth of the riverbed would be 3.39 m.

### 3.4 Scour model experiment method

The scour model experiment simulates the boundary and hydrodynamic conditions of a prototype river according to the mechanic similarity principle of flow and sediment transportation. The maximum scour depth of the riverbed can be forecasted under the steady flow conditions in the experiment.

#### 3.4.1 Scope of model

The model boundary enclosed a distance of approximately 0.7 km of the Fenghuahe River from Ling Bridge to the river junction, approximately 0.7 km of the Yaohe River from...
Jiefang Bridge to the three-river junction, and approximately 0.7 km of the Yonghe River from the river junction to the fishing boat plant. The initial profiling of the mobile bed model was determined according to the measured bathymetric data obtained in May 2008. A geometric scale of 1:80 was adopted. Clayed sawdust was used as the model sediment. The dry density of the sawdust was 0.60 kg/m$^3$, and the medium diameter of the sawdust was 0.45 mm. The reach from Ling Bridge to Yonghe Bridge was designed to be a mobile bed model. Two velocity measurement cross sections were chosen, each of which consisted of three measurement points. Five cross-stream topographic measurement sections were set, each of which consisted of three bathymetric measuring points. The scope of the model and position of measurement sections are shown in Fig. 4.

![Schematic diagram of scour model](image_url)

**Fig. 4** Schematic diagram of scour model

### 3.4.2 Model validation

In order to ensure the similarity of the model river with the prototype river, the fluid velocity and tidal level of the model river were validated against data recorded at the site. Observed hydrologic data from 4:00 am on April 29, 2006 were used to validate the flow velocity of the model river. The flow discharge of the Fenghuahe River and the Yaohe River were 705 m$^3$/s and 72 m$^3$/s, respectively, and the tidal level of the Yonghe River was 0.23 m. The validation test of flow velocity is shown in Table 2. The errors of the flow velocities between the model river and the prototype river were less than 0.03 m/s. The simulated flood process of a 200-year return period flood of the Fenghuahe River using the mathematical model was also used to validate the tidal level of the model river (Yan and Jin 2008). A comparison between the simulated and experimental levels is shown in Table 3. The errors between the model and prototype tidal levels were less than 5 cm. This conformed to the required precision of the project design.

<table>
<thead>
<tr>
<th>Velocity measurement point</th>
<th>Prototype river flow velocity (m/s)</th>
<th>Model river flow velocity (m/s)</th>
<th>Relative error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. 1</td>
<td>1.15</td>
<td>1.17</td>
<td>1.48</td>
</tr>
<tr>
<td>No. 2</td>
<td>1.27</td>
<td>1.25</td>
<td>–1.27</td>
</tr>
<tr>
<td>No. 3</td>
<td>1.21</td>
<td>1.23</td>
<td>1.40</td>
</tr>
</tbody>
</table>

*Table 2 Flow velocity validation of prototype river and model river*
Table 3 Validation of simulated and experimental water levels

<table>
<thead>
<tr>
<th>Location</th>
<th>Simulated water level (m)</th>
<th>Experimental water level (m)</th>
<th>Error (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>300 m upstream of Jiangxia Bridge</td>
<td>2.15</td>
<td>2.12</td>
<td>–0.03</td>
</tr>
<tr>
<td>500 m upstream of Xinhe Bridge</td>
<td>2.16</td>
<td>2.13</td>
<td>–0.03</td>
</tr>
<tr>
<td>300 m upstream of Yonghe Bridge</td>
<td>2.05</td>
<td>2.07</td>
<td>0.02</td>
</tr>
</tbody>
</table>

3.4.3 Result of scour model experiment

To forecast the maximum scour depth of the riverbed above the subway tunnel, a flow with the maximum discharge of a 200-year return period flood was modeled. The northern route scheme was taken as an example. After the river channel was scoured for a period of time, the maximum scour depth and the lowest elevation of the riverbed were 4.04 m and –10.53 m, respectively. They were situated 88 m from the left bank. Fig. 5 shows the initial bathymetry and the scour depth.

Fig. 5 Results of scour model experiment

3.5 Numerical simulation method

In this section, a two-dimensional tidal current and sediment transportation model for simulating the fluvial process of the Fenghuahe River is described. The mathematical model was applied to assess the maximum scour depth.

3.5.1 Establishment of mathematical model

The governing equations of the two-dimensional tidal current and sediment transportation model in generalized curvilinear coordinates include the flow and sediment governing equations. The flow governing equations are well established (Xie et al. 2006). The sediment governing equations were discretized on the collocated grid system using the finite volume method, which can be described as follows:

The sediment continuity equation is

\[
\frac{\partial \left( \frac{\partial HS}{\partial \xi} \right)}{\partial t} + \frac{\partial U_{\xi} HS}{\partial \xi} + \frac{\partial U_{\eta} HS}{\partial \eta} = \frac{\partial}{\partial \xi} \left[ DJ \left( q_{i1} HS_{\xi} + q_{i2} HS_{\eta} \right) \right] + \frac{\partial}{\partial \eta} \left[ DJ \left( q_{i3} HS_{\xi} + q_{i4} HS_{\eta} \right) \right] - J \alpha \omega (S - S_{s}) + JqS_0
\]

(2)
The riverbed deformation equation is

\[ \gamma' \frac{\partial Z_b}{\partial t} + \xi_x \frac{\partial g_{bx}}{\partial \xi} + \xi_y \frac{\partial g_{by}}{\partial \xi} + \eta_x \frac{\partial g_{bx}}{\partial \eta} + \eta_y \frac{\partial g_{by}}{\partial \eta} = \sum \alpha \omega (S - S_0) \]  

(3)

where \( H \) is the depth-averaged water level (m); \( U_x \) and \( U_\eta \) are the flow velocity components in the \( \xi \) and \( \eta \) directions (m/s), respectively; \( S \) and \( S_0 \) are the sediment concentration and sediment carrying capacity (kg/m³), respectively; \( q \) is the lateral flow discharge in unit area (m/s); \( S_0 \) is the lateral sediment concentration (kg/m³); \( D \) is the coefficient of turbulent viscosity; \( \alpha \) is the coefficient of saturation recovery; \( \gamma' \) is the dry density of sediment (kg/m³); \( J \) is the Jacobian coefficient; \( q_{11} = \xi^2_x + \xi^2_\eta \), \( q_{12} = \xi_\eta + \xi_\eta \), and \( q_{22} = \eta^2_x + \eta^2_\eta \); \( Z_b \) is the elevation of the riverbed (m); \( S_\xi, S_\eta, \xi_x, \xi_\eta, \eta_x, \eta_\eta \) are partial derivatives, where \( S_\xi = \partial S / \partial \xi \), \( S_\eta = \partial S / \partial \eta \), \( \xi_x = \partial \xi / \partial x \), \( \xi_\eta = \partial \xi / \partial y \), \( \eta_x = \partial \eta / \partial x \), and \( \eta_\eta = \partial \eta / \partial y \); \( \omega \) is the sediment settling velocity (m/s); and \( g_{bx} \) and \( g_{by} \) are the bed load sediment transport rate components in the \( x \) and \( y \) directions (kg/s), respectively.

### 3.5.2 Sediment carrying capacity formula

According to the analysis of measured data from the Yonghe River, the sediment carrying capacity formula can be described as follows:

\[ S_* = k \frac{U^{2.1}}{H^{0.7}} \]  

(4)

where \( k \) is the coefficient of the sediment carrying capacity with a value in the range of 6.0 to 7.5, which can be calculated from measured data, and \( U \) is the depth-averaged flow velocity (m/s). The gradation of sediment carrying capacity was adopted based on the model of Dou et al. (1995).

### 3.5.3 Extent of mathematic model

The extent of the mathematical model was developed to enclose a distance of 3.3 km of the Fenghuahoe River reach from Chenglangyan to the river junction, a distance of 3.3 km of the Yaohe River reach from the tidal gate to the river junction, and a distance of 3.0 km of the Yonghe River reach from the river junction to the Qingfeng Thermal Power Plant. The bathymetric data measured in July 2008 were used to create the initial bed profile, and the medium diameters of suspended and bed load sediment were 0.011 mm and 0.016 mm, respectively.

### 3.5.4 Model validation

The prototype flow velocity and tidal level data measured in the Yonghe River from April 28 to 29, 2006 were adopted to validate the mathematical model. Fig. 6 and Fig. 7 show the comparison between the measured and simulated tidal levels and the flow velocities at Jingjia Bridge, respectively. The results show that the maximum error of the simulated tidal level was 4 cm. The deviation percentage of flow velocity was less than 10%, and the flow velocity went in the same direction as the prototype river. The riverbed fluvial process from
November 2005 to July 2006 was simulated with the model. The results show that the simulated amount of sediment deposition in the reach from the river junction to the fishing boat plant was $2.41 \times 10^4$ m$^3$, and the measured amount was $2.89 \times 10^4$ m$^3$, with a deviation percentage of 18%. The simulated and measured topographic data of the section near Jiangxia Bridge are compared in Fig. 8. This shows that the error was less than 0.15 m, conforming to the required precision of the project design.

3.5.5 Analysis of simulated results

The fluvial process was simulated with the two-dimensional mathematic model. The flood discharge of a 200-year return period flood was used as the hydrologic condition. Taking the northern route scheme of the subway line as an example, the scour process of the riverbed above the subway tunnel is shown in Fig. 9. The model results show that the riverbed of the main channel was scoured by the flood, and that after 70 h of scouring the maximum scour depth and lowest elevation of the riverbed were 1.15 m and –7.8 m, respectively. At the end of the flood (approximately 168 hours later), the maximum scour depth and lowest elevation of the riverbed were 1.77 m and –8.42 m, respectively, and situated 90 m from the left bank.

4 Comparison and discussion

Due to the different application ranges and forecasting precision of the five methods, a
A comparison of the five methods was carried out.

The fluvial analysis method is used to examine the river regime and evolution trend, and according to the historical data of flood discharge, water depth, and scour depth, a regression formula can be established to calculate the scour depth of the riverbed. The research results of the river regime and evolution trend are reliable, but the forecasting precision is confined by the extent of the historical river data. According to recent data, the river regime of the reach above the subway tunnel in Ningbo City was stable and the sediment deposition was principally due to fluvial evolution. The riverbed will not be scoured unless in the event of a flood.

The characteristics and spatial distribution of quaternary strata under the riverbed were analyzed with the geological structure analysis method. The geological structure data can be obtained easily using core samples; however, this method has a lower forecasting precision, and scour behavior is difficult to forecast if the alluvial layer is thick. By using the method to research the subway tunnel in Ningbo City, it was shown that the soil layer ①1-2, below the riverbed, was formed by historical fluvial evolution of the river. The maximum thickness of the soil layer ①1-2 was 4.3 m, which may be the maximum scour depth of the riverbed above the subway tunnel.

The scour formula is developed depending on the measured and experimental data. The method is widely applicable and simple to apply. The instantaneous scour depth is identified, but the fluvial process cannot be identified during the flood process, nor can the influence of the riverbed bathymetry. The forecasting precision of the method is moderate. The results of this method, used to examine the subway tunnel in Ningbo City, showed that the maximum scour depth of the riverbed was 3.39 m.

The physical scour model was built to simulate the riverbed scour by a flood. The model experiment enables the problem to be visualized, and a high precision may be obtained. However, it is expensive to produce, costing a lot of time and space. Using the scour model experiment to research the subway tunnel in Ningbo City, the maximum scour depth of the riverbed above the subway was shown to be 4.04 m.

The mathematical model was established to research the fluvial process. The whole process of riverbed evolution and instantaneous maximum scour depth can be simulated, but the model is complex, and the forecasting precision is related to the model’s precision. The results of this method, used to examine the subway tunnel in Ningbo City, showed that the maximum scour depth of the riverbed was 1.77 m.

A comparison of the five methods is shown in Table 4. To forecast the maximum scour depth of the riverbed above the subway tunnel in Ningbo City, a multi-approach analysis is suggested, and reasonable results can be produced in accordance with local conditions.
Table 4 Comparison of five methods

<table>
<thead>
<tr>
<th>Method</th>
<th>Advantage</th>
<th>Disadvantage</th>
<th>Application range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fluvial process analysis method</td>
<td>Research results of river regime and evolution trend are reliable</td>
<td>Scour formula’s construction and forecasting precision are confined by historical data</td>
<td>Basic research</td>
</tr>
<tr>
<td>Geological structure analysis method</td>
<td>Geological structure data are obtained easily</td>
<td>Forecasting precision is lower, and forecast is difficult if alluvial layer is thick</td>
<td>Secondary research</td>
</tr>
<tr>
<td>Scour formula method</td>
<td>Calculation is simple and it is widely applicable</td>
<td>Effect of riverbed topography cannot be reflected</td>
<td>Pipeline projects</td>
</tr>
<tr>
<td>Scour model experiment method</td>
<td>Experiment is visible and there is a high precision of forecasting</td>
<td>Model is expensive, costing more time and space</td>
<td>Subway and tunnel projects</td>
</tr>
<tr>
<td>Numerical simulation method</td>
<td>Instantaneous maximum scour depth of riverbed can be simulated</td>
<td>Forecasting precision is related to model’s precision</td>
<td>Subway and tunnel projects</td>
</tr>
</tbody>
</table>

5 Conclusions

Five methods, including the fluvial process analysis method, geological structure analysis method, scour formula method, scour model experiment method, and numerical simulation method were used to forecast the maximum scour depth of a riverbed above a subway tunnel. In order to analyze the application ranges and forecasting precision of the methods, a subway tunnel project to be constructed in Ningbo City was taken as an example and the aforementioned five methods were used to forecast the maximum scour depth. The river regime and evolution trend were examined with the fluvial process analysis method, which was the base method of forecasting the scour depth of the riverbed. The calculation results of the scour model experiment method and the numerical simulation method were reliable, and the two methods can be applied to subway tunnel projects passing underneath rivers. The forecasting precision of the scour formula method is less accurate than that of the scour model experiment, and it can be a research method for lower risk projects such as pipelines. The geological structure analysis method has low precision in the calculation results, and it can be a secondary research method, used in combination with other methods. To forecast the maximum scour depth of the riverbed above projects including subways, pipelines, and so on, a multi-approach analysis is suggested.

References


