Study on Limit Scouring of Maliuzhou Waterway: A Case Study of the Cross Gate Tunnel Project

Pengfei Huang¹, Hua Wang¹, Tiansheng Wu¹ and Hua Wang*²

¹ Department of River & Coastal Engineering of The Pearl River Hydraulic Research Institute, Guangzhou, Guangdong, 510000, China
² Corresponding author’s e-mail: wanghai@pearlwater.gov.cn

Abstract. Based on the analysis of the water and sediment characteristics of the Maliuzhou Waterway, this paper establishes a local physical model near the project and a mathematical model of two-dimensional tidal sediment with reasonable hydro-logical and sediment parameters of river scouring so as to simulate the river scouring under the extreme conditions of the Maliuzhou Waterway. Based on the calculation results, this paper divides the fracture surface and longitudinal section of the river near the project and analyzes its fracture surface, section and channel layout so as to explore the characteristics of the river scouring under the extreme conditions of the Maliuzhou Waterway. This study shows that under extreme conditions, the deepest scouring of the Maliuzhou Waterway is in the main channel, and the hydrodynamic axis and the talweg of the river channel show little change.

1. Project Overview

Hengqin, on the west bank of the Pearl River, is located in the southeastern part of Zhuhai City, adjacent to Hong Kong and Macao. It is also at the intersection of "one country, two systems" and the "internal and external radiation". Therefore, it boasts great geographical advantages. As one of the seven external channels in the Urban Master Plan of Hengqin New District (2014-2020), the Cross Gate Tunnel Project, running from the Maliuzhou Waterway to Hengqin Island, is about 1200m from the downstream of the Hengqin Bridge. The Cross Gate Tunnel Project is oblique to the water supply pipe tunnel for Macao. For this project, the immersed pipe method cannot be well applied. Therefore, the shield method is used to cross the Maliuzhou Waterway. The diameter of the lower through pipe is 15.2m, which is quite large for the tunnel constructed using the domestic shield method. The traversing location of the tunnel is shown in Figure 1.

The design of the tunnel running through a waterway needs to consider the factors such as the tunnel depth and investment cost. Therefore, the characteristics of the tunnel reach and especially study on limit scouring, are of vital importance. As a tributary of the Modaomen Waterway, one of the eight major gates of the Pearl River, Maliuzhou Waterway has the flood discharge accounting for about 12% to 18% of the runoff of Modaomen Waterway. After a large-scale remediation project related to Modaomen Waterway in the 1990s, the water and sediment conditions of the Maliuzhou Waterway have undergone significant changes, which will subtly affect its riverbed erosion and sedimentation. At the same time, the Modaomen Waterway is affected by not only the upstream water conditions, the changes in the tides outside the entrance, and the changes in the water and sedimentation of the main tributaries, but also human activities such as the remediation project of the neritic zone of Modaomen Waterway and the Maliuzhou Waterway, so it has complicated characteristics. Therefore, study on the limit...
scouring of the Maliuzhou Waterway under complex conditions is of great practical significance to nearby tunnels.

**Figure 1. Location map of the Cross Gate Tunnel Project.**

### 2. Characteristics of Water and Sediment near the Project

#### 2.1. Runoff

This paper conducts correlation analysis of the maximum falling tide volume of Denglongshan Station of Modaomen Waterway and Maliuzhou Waterway based on the measured data from March 25 to 29, 1997, February 7 to 15, 2001, July 21 to 29, 2001, and June 17 to 18, 2016 so as to obtain the variation trend of the split ratio. As can be seen from Table 1:

1. The split ratio of the maximum tidal current of the Maliuzhou Waterway increases with the increase of the maximum tidal current of Denglongshan Station;
2. The split ratio of the maximum tidal current of the Maliuzhou Waterway gradually decreases from 1997 to 2016.

**Table 1a. Table of maximum ebb flow relation (unit: m³/s)**

| Maximum ebb flow | 1997.3 | 2001.2 |
|------------------|--------|--------|
| Flow of Denglongshan: Q₁ | 3000 4000 5000 6000 2500 3000 4000 5000 6000 7000 |
| Flow of Maliuzhou Waterway: Q₂ | 430 780 1120 1480 160 320 620 930 1230 1540 |
| Q₁/Q₂×100% | 14.3 19.5 22.4 24.7 6.4 10.7 15.5 18.6 20.5 22 |

**Table 1b. Table of maximum ebb flow relation (unit: m³/s)**

| Maximum ebb flow | 2001.7 | 2016.6 |
|------------------|--------|--------|
| Flow of Denglongshan: Q₁ | 5000 6000 7000 8000 9000 10000 11000 12417 |
| Flow of Maliuzhou Waterway: Q₂ | 780 1000 1230 1460 1680 1900 2140 1843 |
| Q₁/Q₂×100% | 15.6 16.7 17.6 18.3 18.7 19 19.5 14.84 |
2.2. Current
For the flow, water level and velocity characteristics near the project based on the measured data of the Maliuzhou Waterway in the upper reaches of the project from July 23 to 29, 1994 (flood), September 23 to 29, March 25 to 30, 1997, see Table 2.

From the measured data of large and small tides in September 2012, the water flow near the project rises under the restraint of both sides while the falling tide is reversing current. The flow velocity of the downstream cross section is slightly smaller than that of the upstream, and the velocity of large tides is larger than that of smaller ones. During the period of large and small tides, the falling tide velocity of the water in which the project is located is higher than its rising tide velocity. The maximum falling tide velocity is about 1.3~2.3 times that of the maximum rising tide velocity, and the average falling tide velocity is about 1.2~2.1 times that of the average rising tide velocity.

Table 2. Table of flow, water level and flow velocity characteristics of Maliuzhou station

|                | 1994.7 (Flood) | 1997.9 (Medium) | 1997.3 (Low) |
|----------------|---------------|----------------|-------------|
| Maximum flow (m$^3$/s) | 2410          | 1370           | 1070        |
| Maximum ebb velocity (m/s) | 1.30         | 0.85           | 0.65        |
| Water level corresponding to the maximum ebb (m) | 0.83         | 0.22           | 0.16        |

Figure 2. Figure of measured tidal current vector in waters near the project (2012.9)

2.3. Sediment
The Pearl River features large runoff and small amount of sand, with suspended sediment as the main sediment transported. Due to the large runoff, the average annual sediment transport is as high as 75.7 million tons in many years. The amount of sediment transport changes significantly with time. The average annual sediment transport in the 1960s, 70s, 80s, 90s and the first 10 years of the 20th century is 82.2, 91.8, 92.5, 75, 34.5 million tons, respectively, while that decreases sharply after 2000.

The sediment entering the Pearl River estuary is mainly suspended sediment with only a small amount of bed load. The suspended sediment mainly comes from the upstream river runoff, such as Xijiang River, followed by the Beijiang River and the Dongjiang River. According to analysis, every year, there is about 80% sediment entering the Pearl River Delta that is transported outside, while about 20% remains in the entrench. In the flood season, due to the large runoff and high sediment concentration, there is basically no marine sand, and the sediment transport accounts for about 95% of the annual total.
In the dry season, the river runoff is small and the sediment concentration is low. The amount of sediment transport is relatively small, so the effect of tidal current transport is enhanced. Marine sediment exists, but little in quantity. It can be seen that the change of river bed erosion and sedimentation mainly occurs in the flood season.

Based on the sampling data of the bed material near the project of the Pearl River Hydraulic Research Institute on April 17, 2018, the particle size of surface sediment of the riverbed near the proposed project is between 0.016mm and 0.036mm, and that of the proposed engineering line is basically 0.03mm.

3. Introduction to research methods

At present, the methods for studying the limit scouring of waterways are measured data analysis, physical model test and mathematical model calculation. This paper takes measured data analysis as the basis, while combining the mathematical model and physical model of tidal sediment so as to obtain the limit scouring pattern of the waterway under the condition of different flood frequencies and the most unfavorable tides.

3.1. Introduction to mathematical model

The Maliuzhou Waterway is located in the estuary of the Pearl River Delta, under the dual-influence of the offshore tidal current and the upstream runoff. This paper adopts a two-dimensional tidal control equation in the body-fitted orthogonal curvilinear coordinates and establishes a two-dimensional tidal control mathematical model using ADI method so as to analyze the factors of tidal level, flow amount, flow rate, direction and scouring depth near the project.

3.2. Introduction to local physical model

Based on the research content, the adjustment of the inlet and outlet water flow conditions of the model and the tide control, the research scope of the physical model are set as: the upper boundary is about 6km above the upper reach of Maliuzhou Waterway, from the north side of the sea to the Jiuzhou, and from the upper reach of Wanzai Waterway to the area near the Shijiazui Sluice; the lower boundary is about 5km away from the exit of Cross Gate Waterway on the south side, and from the east side of the sea to 4km east to the airport. With the site conditions the water supply capacity of the laboratory taking into consideration, this model uses a plane scale of 300, a model vertical scale of 50 and the variability of 6 to ensure that the water flow is in the region of quadratic resistance law.

3.3. Hydro-logical conditions of limit scouring

Statistics shows that Maliuzhou Waterway where the project is located has a relatively large flow velocity. The maximum rising and falling tidal velocity of the “97.3” near the Majuzhou Station in the dry season are 0.62 m/s and 0.67 m/s respectively. During the “94.7” flood period, its maximum falling tide velocity is 1.30 m/s. It can be seen that the tidal the falling tide in the dry season is slightly faster than the rising tide, while the falling tide in the flood season is much faster than that in the dry season. Therefore, the unfavorable hydro-logical condition of the limit scouring in the reach is supposed to occur during the flood season. So, the flood period is selected as the hydro-logical condition for the limit scouring calculation.

At the same time, the lower boundary of the model is set as the low tide level corresponding to the tide type of the flood period. According to the existing hydro-logical data of the Pearl River estuary, this paper takes the “2005.6” flood tide type as the lower boundary tide type for limit scouring calculation during the flood season.

Based on the large-scale one-dimensional and two-dimensional joint solution mathematical model of the Pearl River estuary, the maximum flow of Denglongshan Station is derived, thus providing the flow boundary for the local two-dimensional mathematical model of the water near the project.

The maximum flow in 100 years of the project upper reach that encounters the “2005.6” low flood tide in the downstream estuary is the once-in-a-century flow of Denglongshan Station.
The maximum flow in 300 years of the project upper reach that encounters the “2005.6” low flood tide in the downstream estuary is the once-in-three-century flow of Denglongshan Station.

3.4. Sediment boundary conditions and river bed particle size
When calculating the ultimate erosion of the river, this study considers the most unfavorable conditions of river scouring, that is, the scouring of clear water. The riverbed particle size is determined according to the measured bed material, $d_{50}=0.03\text{mm}$.

3.5. Time for limit scouring calculation
According to the two-dimensional tidal mathematical model, when the flow velocity of the river is continuously reduced to a point lower than the bed material at a certain moment, the bed material stops moving, indicating the completion of riverbed scouring in the mathematical model. According to the requirements of the physical model test specification, the scouring test time is set to 2 hours. Since the cross section of the Cross Gate Tunnel is thick with fine and viscous sediment particles, the time for reaching scouring equilibrium state is 2–3 times longer. Therefore, this paper sets the flushing time to 8 hours.

4. Experimental results of limit scouring physical model near the project
The overall characteristics of the once-in-a-century flood scouring terrain are: the deep groove of scouring is on the left bank with the deepest elevation being -13.5m, which is located within the Maliuzhou Waterway, about 600m from the cross section; the deepest elevation of the tunnel section is -11.8m, and its maximum scouring depth is -4.7m compared with the current terrain, and the deepest point of the tunnel section is about 250m~300m away from the left bank; the downstream riverbed elevation increases with elevation, which are always lower than -8.0m.

The overall characteristics of the once-in-300-year flood scouring terrain are basically the same as above, but with slightly larger scouring range. Specifically speaking, the deep groove of the scouring is on the left bank, and the deepest elevation is -14.8m, which is located within the Maliuzhau Waterway, about 600m from the cross section; the deepest elevation of the tunnel section is -12.5m, and its maximum scouring depth is -5.4m compared with the current terrain, and the deepest point of the tunnel section is about 200m~250m away from the left bank; the downstream riverbed elevation increases with elevation, which are always lower than -8.0m.

Results of the limit scouring test show that under the most unfavorable conditions of the flow rate in 300 years, the deep groove forms on the left bank, and the deepest elevation is -14.8m, which is located 600m from the upstream; the deepest elevation of the cross section is -12.5m, and the maximum scouring depth is -5.4m compared with the current terrain, and the deepest point of the cross section is about 200m~250m from the left bank. As the riverbed downstream is gradually widened, the elevation of the river bottom gradually increases.
Figure 5. Topography comparison of physical model tunnel site section

5. Simulation and analysis of limit scouring near the project using mathematical model

Arrange 8 sections perpendicular to the embankment near the tunnel line (Series V, with the section spacing of 80m; from north to south), and arrange 5 sections perpendicular to the center line of the tunnel (Series L, with the section spacing of 100m; from upstream to downstream). For the layout, see Figure 6.

Figure 6. Section layout near the tunnel site

5.1. Morphological changes of fracture surface in the upstream and downstream and nearby areas

For the comparison of the fracture surface of the riverbed before and after scouring of each section in Series V, see Figure 7. Under the topographic conditions of April 2018, the once-in-300-year flood condition is basically consistent with the once-in-a-century flood condition, so this paper adopts the maximum scouring depth under the once-in-300-year flood condition as the limit scouring depth. For the maximum scouring depth and the lowest scouring elevation for each fracture surface near the project under the once-in-300-year flood condition, see Table 3:

1. The lowest scouring elevations of the riverbed in which the fracture surface is located in the vicinity of the tunnel (3#~6#) after the once-in-300-year limit scouring are -13.95m, -13.66m, -13.38m, -13.02m, respectively, which are 215.3~320.1m from the left bank; the maximum scouring depths are 7.26m, 7.18m, 7.04m, 6.85m, respectively, which are 270.7m, 261.0m, 326.4m, 420.3m from the left bank; the lowest point of the riverbed moves 13.7m, 10.8m, 18.6m, 18.4m towards the right bank.

2. The minimum elevations of the riverbed in which the upstream fracture surface is located (1#~2#), after the once-in-300-year limit scouring, are -14.25m and -14.18m, respectively, which are 239.7m and
210.3m from the left bank; the scouring depths are 7.62m and 7.44m, respectively, which are 269.7m and 263.7m away from the left bank; the thalweg moves about 5m towards the right bank.

③ The lowest elevations of the riverbed in which the downstream fracture surface is located (7#~8#) after the once-in-300-year limit scouring are -12.82m and -12.48m, respectively, which are 360.7m and 410.7m from the left bank; the maximum scouring depths are 6.55m and 6.54m respectively, which are 460.8m and 503.6m from the left bank; the deep thalweg moves about 20.5m and 25.2m towards the right bank.

④ The maximum scouring depths of the section (3#~6#) near the tunnel, 3#, 4# and 5# sections after the once-in-300-year section are 7.26m, 7.18m, 7.04m, respectively. That of the 3# section is 270.7m from the left bank and 190.2m from the tunnel; that of the 4# section is 261.0m from the left bank and 106.5m from the tunnel; that of the 5# section is 326.4m from the left bank and 5.5m from the tunnel. Therefore, the maximum scouring depth of 5# section is selected as that of the tunnel site.

Figure 7. Schematic diagram of section shape before and after scour (1#~8#)
Table 3. Maximum scour depth and minimum scour elevation (0.33%, unit: m)

| Section No. | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   |
|-------------|-----|-----|-----|-----|-----|-----|-----|-----|
| Lowest elevation after scouring | -14.25 | -14.18 | -13.95 | -13.66 | -13.38 | -13.02 | -12.82 | -12.48 |
| Corresponding scour depth | 7.51 | 7.36 | 7.13 | 7.06 | 6.81 | 6.37 | 6.35 | 6.37 |
| Distance from lowest elevation to left bank | 239.7 | 210.3 | 215.3 | 232.4 | 308.5 | 320.1 | 360.7 | 410.7 |
| Maximum scour depth | 7.62 | 7.44 | 7.26 | 7.18 | 7.04 | 6.85 | 6.55 | 6.54 |
| Corresponding river bottom elevation | -13.82 | -13.48 | -12.62 | -12.43 | -12.14 | -12.41 | -12.49 | -12.46 |
| Distance from maximum scour location to left bank | 269.7 | 263.7 | 270.7 | 261.0 | 326.4 | 420.3 | 460.8 | 503.6 |

5.2. Morphological changes of longitudinal section of upstream and downstream riverbeds
The morphological comparison of the longitudinal section before and after scouring of each section in series L is shown in Figure 8. As can be seen from the figure, the general morphological change of the riverbed is related to its location. The main channel of the river where the tunnel site is located is quite violent, so the maximum depth reaches 7.04m, while scouring in the near-shore section is slighter.

![Figure 8. Schematic diagram of section shape before and after scour (A#~E#)](image)

5.3. Analysis of trough layout after the limit scouring of the engineering section
The trough layout, shoreline boundary and dynamic axis changes are the main factors affecting river stability. The change in trough layout affects the change of the dynamic axis, which in turn influences
trough layout. Small change of trough layout and dynamic axis has a small impact on river stability, while larger change of trough layout and dynamic axis has a larger impact.

Analysis of calculation results of the sediment mathematical model shows that the trough of the downstream section of the Maliuzhou Waterway has been scoured with the scouring width of about 580m. The main trough suffers scouring the most with the maximum scouring amplitude of 7.04m.

For the thalweg change of the engineering section after the limit scouring when once-in-100/300-year flood encounters the downstream "2005.6" low tide level, see Figure 9. It can be seen that the thalweg position changes only slightly. After limit scouring, the deepest point is still in the left bank. After taking into consideration the evolution factor of riverbed in recent years, the amplitude of thalweg is still the deepest in the left bank. The thalweg amplitude of the river section near the project slightly increases, and the area with large thalweg amplitude is 220m and 560m from the upstream and the downstream of the tunnel. The thalweg amplitude is basically within 30m.

For the dynamic axis change of the engineering section after the limit scouring when once-in-100/300-year flood encounters the downstream "2005.6" low tide level, see Figure 10. It can be seen that limit scouring has the most influence on the main trough, which develops to the bottomlands on both sides. Since the right bank is obviously scoured, the dynamic axis of the river section where the tunnel project is located generally moves towards the right bank, but in a small amount of about 5m.

5.4. Analysis of trough layout after the limit scouring of the engineering section

After the limit scouring of once-in-100/300-year flood, the maximum scouring depth of the riverbed in the middle of the tunnel is about 6.39m and 7.04m respectively. The minimum overburden thickness between the tunnel crossing the Maliuzhou Waterway (Hongwan Waterway) and the current riverbed fracture surface is above 13.22m, thus meeting the requirement for burial depths.

6. Conclusion

Mathematical model calculation shows that the maximum scouring depth of the mid-line riverbed of the combined tunnel after the limit scouring of once-in-100/300-year flood is about 6.39m and 7.04m, respectively, and the physical model limit scouring test shows that of the tunnel axis is 4.70m and 5.40m, respectively. The two results are similar. For safety, it is recommended to take the maximum value of scouring of the fracture surface, using the mathematical model.

This paper studies and predicts the limiting scouring of the Maliuzhou Waterway under the Cross Gate Tunnel while combining the once-in-100/300-year flood and downstream low tide level using the measured data analysis, physical model test and two-dimensional tidal mathematical model. This study shows that the deepest scouring of the Maliuzhou Waterway is concentrated in the main trough of the river channel, and the hydrodynamic axis and the talweg of the river channel do not changed much after limit scouring.

It should be pointed out that the measured particle size of surface bed material is used as the median particle size in numerical simulation. However, under practical conditions, as the river channel is continuously scoured, the sediment particle size is gradually coarsened, so it is a relatively safe assumption that the river bed particle size remains constant during simulation. At the same time, due to
the lack of measured data of sediment concentration in the river channel, it is also a safe assumption to use the clean water for scouring in the Maliuzhou Waterway. Future study is suggested to strengthen the observation of sediment and channel erosion and deposition in relevant river sections so as to provide conditions for studying the law of river sediment.

References

[1] Petts, G. E. (1979). Complex response of river channel morphology subsequent to reservoir construction. Progress in Physical Geography, 3(3), 329-362.

[2] Lewin, J., Hughes, D., & Blacknell, C. (1977). Incidence of river erosion. Area, 177-180.

[3] Lan, H., Ma, B., Zhang, Y., & Shu, B. (2014). Buried pipe affected by river erosion when crossing the Yangtze River. Journal of Pipeline Systems Engineering and Practice, 6(3), A4014002.

[4] Mustafić, S., Manojlović, P., & Milošević, M. V. (2013). Extreme Erosion Rates in the Nišava River Basin (Eastern Serbia) in 2010. In Geomorphological impacts of extreme weather (pp. 171-187). Springer, Dordrecht.

[5] Lin, F., Wang, B. (2015). Prediction of limit scour depth in cross - river tunnel section of Hengzhou channel in Modaomen. China water transport (second half), (7), 67.

[6] Yang, Y., Yang, L, L. (2014). Research on the limit scour of Guangzhou to Foshan road through Chen cun channel tunnel project. Guangdong water resources and hydropower, (9), 6-11.

[7] Yang, L, L., Xu, F, J., Wang, Y, H., Liu, J, Y. (2005). Study on the coupling model of one-dimensional and two-dimensional flow and salinity in tidal river network area. Proceedings of the 7th national conference on hydrodynamics and 19th national symposium on hydrodynamics (volume ii).

[8] Wu, M, W., Yan, L., Hu, X, Z., Tu, X, Y., Zhou, J, Y. (2012). Prediction of the limit scour depth in Nanning tunnel. Pearl River, 33(1), 47-51.

[9] Yang, F., He, Y. (2010). Numerical simulation of the limit scour in the section of Guangfo crossing tunnel. Pearl River, (2), 14-18.

[10] Lai, X., Yin, D., Finlayson, B. L., Wei, T., Li, M., Yuan, W., ... & Chen, Z. (2017). Will river erosion below the Three Gorges Dam stop in the middle Yangtze. Journal of hydrology, 554, 24-31.

[11] Wong, J. S., Freer, J. E., Bates, P. D., Sear, D. A., & Stephens, E. M. (2015). Sensitivity of a hydraulic model to channel erosion uncertainty during extreme flooding. Hydrological processes, 29(2), 261-279.

[12] Yuan, W., Yin, D., Finlayson, B., & Chen, Z. (2012). Assessing the potential for change in the middle Yangtze River channel following impoundment of the Three Gorges Dam. Geomorphology, 147, 27-34.