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Settlements of immersed tunnel on soft ground: A case study

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ABSTRACT: This paper focuses on the settlement analysis of immersed tunnel on soft ground. Even under careful design, immersed tunnel may have problems of excessive settlement and the resulting concrete cracking or structure leakage during operation period. Yongjiang Tunnel, the first immersed tunnel on soft ground in mainland China, is taken as a case study. The monitored settlement data after a 16-year service is first displayed and analyzed, then a 2D numerical model is built to simulate the ground settlement deformation from tunnel construction to long-term tunnel operation. The effects of back-silting on the stiffness of the foundation layer and further on the settlement is quantitatively analyzed, and the advices on settlement control for immersed tunnel on soft ground are provided.

1 INTRODUCTION

1.1 *Settlement of immersed tunnel*

Immersed tunnels are built under waterways and they are usually better than other crossings like bridges or bored tunnels. Tunnels are superior to bridges mainly in that they do not disturb ship navigation, especially for busy water channels. Bored tunnels usually have a minimum buried depth for safety and thus bored tunnel are usually designed to a certain depth below the river bed, which can increase the buried length of the whole tunnel. Immersed tunnel consists of prefabricated elements (usually around 100 meters long) which are connected underwater with special rubber gaskets. The immersed tunnel structure can be placed directly on the trench excavated on the shallow river bed, and no minimum buried depth is needed, unlike bored tunnel, so when at the same construction site, the total length of an immersed tunnel generally can be shorter than that of a bored tunnel. Also, immersed tunnels are usually factory-prefabricated element by element and then flowed to the immersion site. They have less joints than bored tunnel, which reduce the water leakage risk; what's more, critical sub-projects of immersed tunnel construction, like trench excavation and element fabrication can go simultaneously, and this can save much time and reduce project cost (Lunniss & Baber, 2013).

Immersed tunnels are mostly constructed under canals and waterways, especially where no water navigation interference is allowed. There are more than 200 immersed tunnels in the world, with most of them in the North America, Europe and Asia. For example, in the Netherlands alone, there are more than 30 immersed tunnels. More immersed tunnel projects, including the 6.0km Hongkong-Zhuhai-Macao Bridge Tunnel, the 18km Fehmarnbelt fixed road and rail link, et al are being constructed or designed for fixed links or underpasses beneath waterways (Hu, 2015; Pedersen, 2018)

Generally, immersed tunnel construction will firstly remove part of soil when doing the trench excavation, and the tunnel body is generally lighter than the soil it replaced, so it is easy to infer that pressure on foundation should be within a small level as not to cause large settlement. However, many immersed tunnels have suffered excessive settlement, which is, at least, much larger than the anticipated value in the primary project design. For some projects on soft ground, serious settlement even has caused troubles for normal operation. Some immersed tunnels on soft ground have suffered significant differential settlement and even cause subsequent problems such as leakage, concrete cracking or even damage of joint waterproofing Gasket.

For example, Kiltunnel in Netherlands suffered a serious differential settlement at element joints, and this further caused leakage inside the tunnel and the leaked water freezed to ice in winter, which risk the traffic safety. More information on immersed tunnel settlement are provided by Grantz (Grantz, 2001).

The settlement of immersed tunnel is mainly related to geological conditions, construction quality and design methods. Due to the complexity and uncertainties from project design and construction, immersed tunnel settlement is mostly studied from field measurement and qualitative analysis. For example, Grantz (Grantz, 2001a,b) summarized the immersed tunnel settlement issues, including the potential factors which cause excessive settlement, the effects of settlement on the tunnel structure and provide settlement data of 15 immersed tunnel projects. Settlement problems are more or less can be explained qualitatively by the reasons listed, which include sub-soil conditions, foundation treatment methods, tunnel section, siltation, et al. It should be noted that settlement is inevitable, or inherent, since it is impossible or cost-effective to make soft ground an absolutely rigid body without any deformation, but technically possible to keep settlement within a safety limit. Some researchers have collected settlement data of more than 20 immersed tunnels (Shao, 2003), with most conclusions from (Grantz, 2001b), and concluded that settlement of immersed tunnel are affected by many complex reasons. When founded on soft ground, immersed tunnel is more likely to settle excessively, and special foundation treatment is often needed. For example, the foundation of High-Speed Railway immersed tunnel should be well treated. To mitigate the risk of excess settlement on soft ground in Netherlands, the subsoil was firstly pre-loaded on top with a 6-m thick sand layer, and this accelerated the consolidation rate of soft clay and improve the strength of soil. The final settlement value is within design limit (Mortier, 2013).

In this paper, long-term settlement of Yongjiang immersed tunnel is quantitatively studied. This tunnel is the first tunnel on soft ground in mainland China that constructed with immersion method, and it served as an experimental trial for future immersed tunnel construction. The rest of the paper firstly summarizes the main factors which cause excessive settlement, and then Yongjiang tunnel, in Ningbo, China, is taken as a case study. This tunnel was opened to traffic in 1995 and after a more-then-decade service, very significant settlement occurs, which seriously affects the structure performance. In the case study, settlement of Yongjiang tunnel after a 16-year of service is analyzed, then potential reasons which results in such high settlement are analyzed. Secondly, a numerical model is built to simulate the deformation behavior of immersed tunnel from construction to long-term service period. The key construction steps including trench excavation, gravel pavement, tunnel element placement, backfilling, back-silting of river bed in operation period, are considered.

2 POTENTIAL TRIGGERS FOR IMMERSED TUNNEL SETTLEMENT

2.1 *Uniform settlement or differential settlement*

Uniform settlement, which usually refers to the settlement of the structure as a whole rigid body. Structure loading on elastic foundation or ground will trigger settlement definitely, since the stiffness of the soil medium is limited, though sometimes very large. But uniform settlement generally does not affect the structure safety much if within a certain limit. For immersed tunnel, uniform settlement of tunnel body will not cause rotation of tunnel elements and no concrete cracking, but however, almost all the tunnel experience differential settlement.

Differential settlement means different settlement values of the tunnel body, this usually leads to the element rotation, joint opening, cyclic compression and expansion of rubber gasket, and internal force of the tunnel body. what's more, the subsequent problems like concrete cracking, leakage, et al, will deteriorate the performance of immersed tunnels (Grantz, 2001a).

It should be noted that because foundation stiffness is limited, settlement of immersed tunnel is unavoidable since the pressure on underlying stratum. Anticipated settlement within safety margin is not troublesome to structure safety. But What we are interested is the unexpected excessive settlement which harms the structure significantly.

As pointed out by (Grantz, 2001a), the factors related to immersed tunnel settlement (or, excessive settlement) can be summarized as the follows:

1) Sub-soil conditions. Generally, consolidated sandy layer has a lower settlement value compared with compressible clayey soil, and the latter also needs a longer time to reach a stable final settlement.
2) Siltation. Siltation may accumulate on the trench surface and may cause serious differential settlement, this is especially severe for immersed tunnel founded by sand-jetting or sand-flow method.
3) Method of tunnel foundation construction. Immersed tunnel is generally founded on sand layer (by sand-jetting or sand-flow after the element placement) or screeded gravel bed (before element placement), such as the Øresund tunnel, the Hongkong-Zhuhai-Macao bridge tunnel, et al. both of the methods are widely used and have different settlement control ability.
4) Surcharge. This may include the backfill on top of the tunnel and the increasing heavy traffic loading which exceeds the designed target. Back-silting on the river bed usually causes significantly large settlement, and periodic dredging of the tunnel location has been performed in many tunnel projects.
5) Trench dredging methods. Commonly, hydraulic cutter-head suction dredges and/or clam-shell bucket dredges are used to excavate the tunnel trench. The latter may tend to leave a more irregular bottom with larger voids that can take longer for the foundation material to fill and stabilize.
6) Tunnel geometry. Tunnel with octagonal section has a narrower contact width than its projected plan width, while rectangular section has the same contact width as the section width. Large contact area usually means lower foundation pressure and hence a lower settlement.
7) Large tidal variation. Under certain circumstances, large amplitude tidal variation may also cause settlement of sands by their gradual compaction due to daily oscillations in pore pressure. If covered by a clay layer that slows the relief of pore pressures, the upper layers of sand may cause oscillation of the supporting ground.

Generally, final settlement of immersed tunnel is affected by multiple factors and analyzing the effects of each factor are usually too complicated. However, some basic design calculation and modelling, plus a good assurance of construction quality control will help to reduce the structure damage from excessive settlement.

3 SETTLEMENT ANALYSIS OF YONGJIANG IMMERSED TUNNEL

3.1 *Project introduction*

Yongjiang tunnel, which is in Ningbo, China, is located on very soft clayey ground. This tunnel crosses under Yongjiang River, and was the first immersed tunnel on soft ground in mainland China, the construction of Yongjiang tunnel started in June, 1987, and it was opened to traffic in 1995. Longitudinally, Yongjiang tunnel is 1019.97m in total, including the cast-in-place approaches on both sides by cut and cover method, and central immersed section(420m). The immersed tunnel consists of 5 elements (85m×3+80m×2) which are connected by immersion joints. The prefabricated tunnel section has a rectangular cross-section with 11.9m wide and 7.65m high, with dual lanes plus a 1.25m wide side-way for operation inspection (Xie, 2014). It should be noted that Yongjiang Tunnel has a small cross-section, but this project served as a trial for immersed tunnel practices in mainland China. The experience gained in construction of this small tunnel is of great help for the future immersed tunnel engineering practice in mainland China.

Yongjiang tunnel was founded on grouted cementitious material, underlaid by a coarse gravel layer. Firstly, the trench was excavated and then a gravel bed is formed by dumping the coarse gravel on the trench bottom. Then tunnel element is placed on the temporary support and then gap between the element and the gravel layer (40cm) is backfilled with grouting materials (com-posed of cement, fly-ash, bentonite, fine sand and chemical admixture). And the

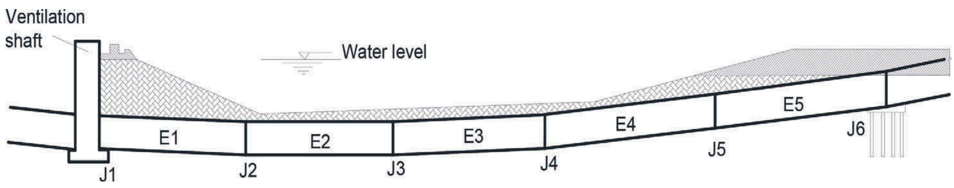

Figure 1. Longitudinal profile of Yongjiang Tunel.

element is fully released to set on the grouted bed. The temporary jacket below water is removed. Then backfill the gap around the tunnel element until to the natural river bed grade. The backfill acts as protective layer as well as ballast against buoyancy.

3.2 *Geological conditions*

The underlaying ground of Yongjiang Tunnel mainly consists of muck soil, mucky clay and medium-sized sand from top down. The muck soil has a thickness ranging from 10–13m, and mucky clay has a thickness of about 5–6m, then underlaid by sand layers interbedding with muck and clay. The muck soil is highly compressible and with low strength, and standard penetration test show a value of 1–2; the tunnel is designed to be placed within saturated muck soil layer, as it was calculated, in the tunnel design, that pressure on foundation bed was very low.

After 11-years of service, Yongjiang Tunnel generally works well, no vital structure damage occurred. But some problems arised, including tunnel structure cracking and water leakage, differential settlement between elements, damage of pavement, reinforcement corrosion on the wall at the approach section, et al. From October 2007 to March, 2008, the tunnel was closed for a major maintenance repair. The repair work mainly includes the grouting at some leaking points to seal the leakage, repairmen of the pavement, strengthen the pillar by expanding the section. As the immersion joint E5 settle significantly, the Gina and omega gasket are inspected, the cover on the wall outside the immersion joint is removed and the joint gap is measured. This can infer the compression status of Gina gasket and asses the waterproofness of immersion joints. And a structure health monitoring network is formed at the finishing of tunnel repair (Li, 2011).

3.3 *Settlement data analysis*

The tunnel structure settlement is monitored since its open to traffic. Vertical settlement is measured by hydraulic static leveler with fixed bolts on the tunnel wall. Until now, the tunnel has undergone a significant settlement and this caused concrete cracking. The Figure 2 shows the tunnel settlement profile at joints locations. After 16-year of operation, the tunnel suffers a serious settlement, with the maximum settlement magnitude about 86mm at immersion joint 5 between Element 4 and 5. While joint 4 at Element 3 and 4 reached a maximum about 56mm (Xie, 2014). This settlement level is well beyond the anticipated value in project design stage.

According to the administration of tunnel operation, excessive settlement of this immersed tunnel may be attributed to the following reasons (Xie, 2014):

1) the underlying soil is extremely soft, highly plastic and compressible, which needs a long time to consolidate under loading.
2) the surcharge from heavy river bed back-silting. Yongjiang Tunnel is located at a delta area and suffered serious siltation, the siltation accumulates at top of the tunnel element and added to the loading, which further causes consolidation of sub-soil and hence an increased settlement.
3) the change of tides causes a varying in the porous pressure in the soil stratum, and lead to the tunnel structure fluctuation.

But the problem is, to what extend did the back-silting surcharge add to the total settlement? Is it the problems of siltation during tunnel immersion, say trench excavation, that

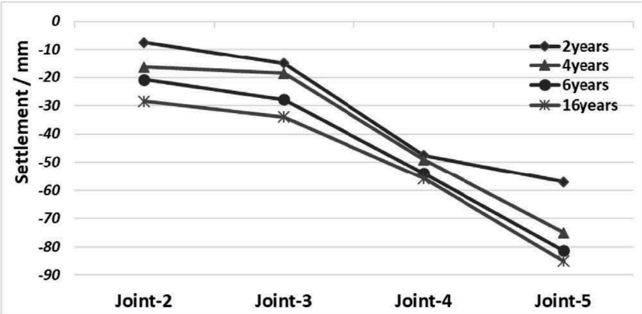

Figure 2. Joint settlement of Yongjiang Tunnel.

cause the most settlement, or rather the surcharge loading from back-silting at operation stage? This calls for a careful study.

3.4 *Numerical simulation*

In this section, a 2D numerical simulation model is built in PlaxisV8.5 to calculate settlement of immersed tunnel through the whole stage, from trench dredging, underwater gravel bed formation, tunnel element placement, backfill to natural river bed grade, back-silting in operation stage. Also, sensitivity analysis of stiffness of the bed on the settlement is analyzed.

During the immersed tunnel construction, underlaid soils are disturbed by a "unloading-reloading" process. This is because trench dredging usually removes the shallow subsoil and rebound occurs at the trench bottom, hence the unloading effects, then coarse gravel is dumped to form a relatively stiff bed, which adds a partial loading on the sub-soil and cause settlement. For tunnel with grouted bed, the element is released on the grouted bed layer and this adds to some loading on the sub-soil; then backfilling is performed, and this further increases loads on the sub-soil as well, as referred to be a reloading process. The back-silting at service stage also adds to the loading which results in long-term settlement, periodic dredging operation will reduce the loading, which may lead to a small rebound of the subsoil. During the unloading of trench excavation, negative porous pressure occurs and the disposition of this negative pressure may last for months, which is accompanied by the trench bottom rebound.

For engineering practices, we hope the subsoil to consolidate fast and most of the total settlement occurs within construction rather than operational period. For sandy soil, usually consolidation occurs constantly and secondary settlement in long-term is expected to be low. But for clayey ground, things are usually quite different, sometimes foundation treatment, such as pre-loading or soil improvement, is performed to accelerate consolidation, this is especially for clayey ground. If we want to consider the final settlement in the operation stage more accurately, long-term soil consolidation is necessary to take into account, rather than only based on elastic soil body.

3.4.1 *Key modelling parameters*

A 2D numerical model is built to simulate the settlement of tunnel structure from trench excavation to backfill, and back-silting during operation stage. The underlying strata analyzed include a muck layer, mucky clay and sandy layer. The trench depth is set as 10m below river bed level, slop of the trench is 1:3 from bottom to 1:4 and then changed to 1:7 till the natural river bed. The tunnel element is designed to lay in the muck layer, since the tunnel bottom pressure was considered to be low in the preliminary design. Here the tunnel structure has an absolutely higher rigidity compared with sub-strata, so tunnel structure deformation is not simulated, only the vertical settlement of tunnel bottom is considered.

The ground strata properties used for numerical modelling is shown in Table 1, since elastic modulus for the Hardening Soil (H-S) model here were not available from site investigation directly, they are set to be 2 times the compression modulus obtained from a confined consolidation test in the investigation document. There is a 1.5m-deep gap between the tunnel top and natural river bed, and backfilling is assumed to reach the natural river bed.

Table 1. Mechanical parameters of sub-strata (based on Xie, 2014).

Stratum	Thickness (m)	density ($g*cm^{-3}$)	Yang's modulus (Mpa)	Cohension (kPa)	Internal friction angle (°)
Muck layer	12	1.81	9.7	19	13
Mucky clay	11	1.72	13.5	23	16.1
Medium-sized sand	15	1.87	50	8	30

According to the foundation design, the 1m-thick bed layer under the tunnel consists of a 0.6m-thick screeded gravel bed and a 0.4-m thick grouted material, due to the lack of the properties of the grouted material, the 1-m thick composite layer is simulated as a single gravel layer, with the property parameters adopted from the Hongkong-Zhuhai-Macau Bridge Tunnel project. The static water pressure is taken as static surface loading on the river bed and on the tunnel trench. The simulation step starts from trench dredging, gravel bed formation, tunnel element placement and backfilling (to natural river bed level). In operation period, different back-silting cases on the river bed is simulated as well, the settlement caused by back-silting is analyzed.

3.5 *Settlement result analysis of tunnel*

Figure 3 shows the 2D simulation model in PlaxisV8.5, the modelled cross-section is a typical geological section under the tunnel element 4, and three ground layers are considered, i.e muck layer, mucky layer and sandy layer.

Simulation shows the trench bottom rebounds to a value of 63.8mm when excavation is finished, and this significant rebound is mainly due to the high compressibility of the first muck layer. Usually on soft foundation, rebound of deep excavation is significant, and this rebound can offset the subsequent settlement in tunnel immersion. Gravel dumping cause a loading on the trench bottom, and this cause a settlement of -6.21mm, which is relatively small. The tunnel element placement triggers a settlement of -33.62mm, and this settlement increases to -57.47mm when the trench is backfilled to original river bed level. Note that the absolute settlement of the tunnel bottom is +6.32mm if taking account of the rebound at trench excavation. The results show the tunnel settlement should not be large, at least not so large as to cause a risk of concrete

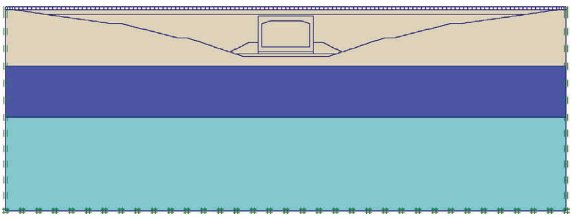

Figure 3. 2D Numerical model of tunnel.

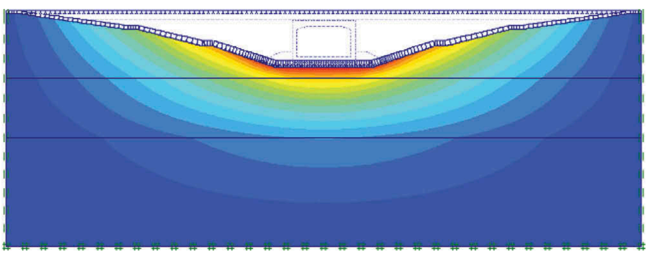

Figure 4. Rebound of immersed tunnel trench bottom due to unloading (maximum as 63.8mm).

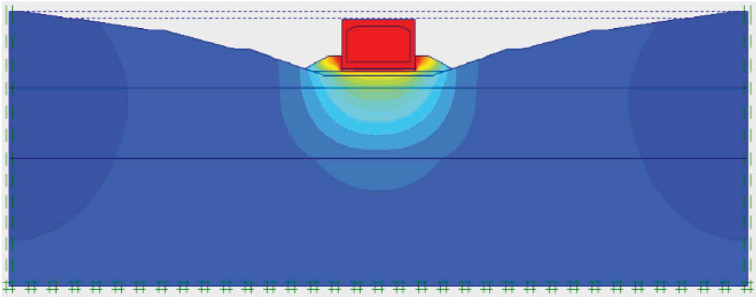

Figure 5. Settlement of tunnel when placed on trench (maximum as 57.6mm).

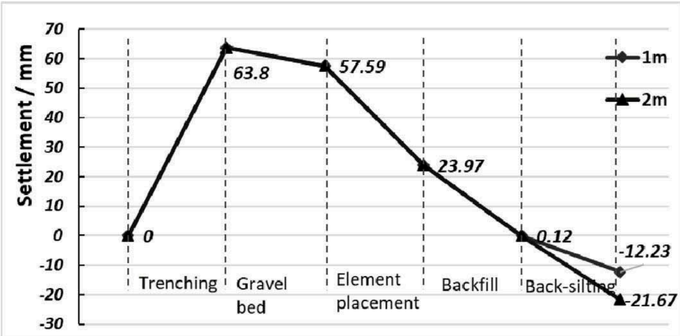

Figure 6. Vertical displacement of tunnel element (positive indicates rebound).

cracking. However, the field monitoring data show there is a surprisingly high settlement value, which is quite beyond expectation. The potential reasons should be quantitatively assessed.

In order to evaluate the potential effects of back-silting on tunnel settlement, different silting loading is considered. Here loading from a 1m-thick and 2m-thick back-silting layer is considered, the newly resulting settlement under 1m-thick back-silting is about -12.23mm, while the corresponding value for a 2m-thick scenario is -21.67mm, that is to say, a unit-meter back-silting generally causes about 10mm settlement of the tunnel. Considering the back-silting, the settlement will increase significantly.

3.5.1 *Effects of bed stiffness*

According to the numerical simulation results, the back-silting alone is not less likely to cause a significant or even shocking settlement (above 80mm) as shown in the field settlement measurement. Since the underwater construction work will bear uncertainties in the foundation quality, and the grouting work control affects the bed stiffness much, as a soft grouted layer will undermine the stiffness of the bed layer right beneath the tunnel bottom. Here a sensitivity analysis is conducted to consider the effects of reduced stiffness on tunnel settlement. In the sensitivity analysis, the elastic modulus of the first underlying layer beneath tunnel bottom is set as 25%, 50% and 75% of the design value in the previous model. And the settlement is recalculated, as shown in Figure 7.

The sensitivity analysis shows that reduction in bed stiffness will cause a much larger settlement compared with the ideally hard bed condition. For example, when the elastic modulus changed to a half, the settlement of the tunnel at backfilling reaches 31.36mm, and this further increases to about 69mm when considered the possible back-silting(2m), this is much closer to the field measured settlement. If considering the reduction of the bed stiffness a step further, say to 25%, the settlement increases much more significantly. Compared with data in Figure 6, it is reasonable to deduce that excessively tunnel settlement is more likely to be, or mainly, caused by the low

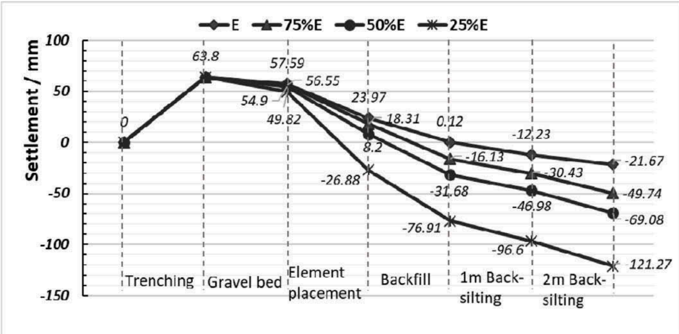

Figure 7. Tunnel settlement under changed bed stiffness.

stiffness of the bed, and this is probably resulting from siltation during trench excavation and element immersion process, hence the importance of trench siltation removal.

4 CONCLUSION

This paper analyzed the settlement of immersed tunnel on soft ground. The settlement of immersed tunnel is mainly related to geological conditions, construction quality and design methods. Long-term settlement of Yongjiang immersed tunnel is quantitatively studied. Settlement of Yongjiang Tunnel after a long-time service is analyzed, then potential reasons which results in such high settlement are analyzed. Secondly, a numerical model is built to simulate the deformation behavior of immersed tunnel from construction to long-term service period. The key construction steps including trench excavation, gravel pavement, tunnel element placement, backfilling, back-silting of river bed in operation period, are considered. Result shows that though back-silting on river bed will significantly increase the settlement due to surcharge effects, the settlement caused by back-silting alone is not likely to reach the measured value. But sensitivity analysis shows bed stiffness reduction causes even larger effects on settlement, which affects the long-term settlement more. The excessive settlement of Yongjiang Tunnel is more likely to be attributed to the bed stiffness reduction, hence siltation control in trench excavation is important for tunnel settlement control.

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