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ARTICLE

Study on Ground Deformation during Shield Tunnel Construction

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ABSTRACT

Through the systematic analysis of the ground settlement generated by the process of shield tunneling, the relationships between ground deformation and construction parameters are studied in this paper. Based on the assumption of linear small deformation, a mathematical model of the relationship between ground deformation and construction parameters is set up. The principle and method of optimization for estimating ground deformation is studied. The actual measured data are compared with the results of theoretical analysis in a case. Considering different ground formations in different construction sites with different adverse effects on surface and underground structures, the ground surface deformations caused by shield tunneling is an aimed topic in this paper. The contributions and research implications are the revealed relationships between the ground deformation and the shield tunneling parameters during construction.

1. Introduction

Shield tunneling has a history of more than 100 years since it was invented by French engineer Marc Isambard Brunel in 1818. It has been developed rapidly and widely used in Germany, the United States, Japan, France and China. Subway shield tunnel construction is carried out under the cover of shield excavation and segment lining of support work [1]. Tunneling affects the surface (such as buildings, bridges, etc.) and underground (urban facilities, tunnels, metro stations, etc.) structures. Therefore, such structures change the behavior of the ground around the tunnel. In urban environments, such deformations have adverse effects on surface and underground structures. Improving the design and construction of underground structures can guarantee the quality, the safety of engineering structures, and coordination between numerical calculations and actual results. The great variety in the factors influencing the surface subsidence (such as the type of soil layering, tunnel depth and dimensions, and tunneling methods) has led to numerous calculations and predictions of subsidence by researchers. All theories related to the surface subsidence calculation how a relationship between the volume of soil that is loosened by tunneling (and fills the excavated space) and the volume of the subsided surface [2]. In general, studies to predict surface subsidence have focused on finite element methods [3], artificial intelligence [4], fuzzy studies [5], and cracking particle method [6,7]. A case of shield tunneling ground surface deformation stimulated by 3-dimational finite element is shown in Figure 1. According to the subway planning and design, the backing ring structure is

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assembled on top of good lining and jacked on the forward thrust to overcome the formation of the shield tunneling of resistance for keeping the shield homogeneous continuous forward [9]. A case of ground surface deformation distribution of shield tunneling is shown in Figure 2. In general, numerical models can provide more complete information than other methods due to their high flexibility. However, incorrect model selection, inaccurate use of parameter values, and misunderstanding of the construction process can lead to erroneous results. Shield tunneling machine includes shield shell, knife plate, brake system, screw conveyor and pressure pump,etc. The main construction process includes installing shield, removing the soil, excavation, propulsion, lining assembling and waterproof [8]. Although many studies have been conducted to determine the amount of ground subsidence due to tunneling in different conditions, investigation of subsidence concerning underground structures is still one of the most challenging issues in the field of geotechnical engineering. Considering the importance of this issue, the present study has investigated the effect of tunneling construction parameters using a mathematical model of the relationship between the ground surface deformation and the construction parameters. Considering different ground formations in different construction sites with different adverse effects on surface and underground structures, the ground surface deformations caused by shield tunneling should be an aimed topic in the still developing research works.

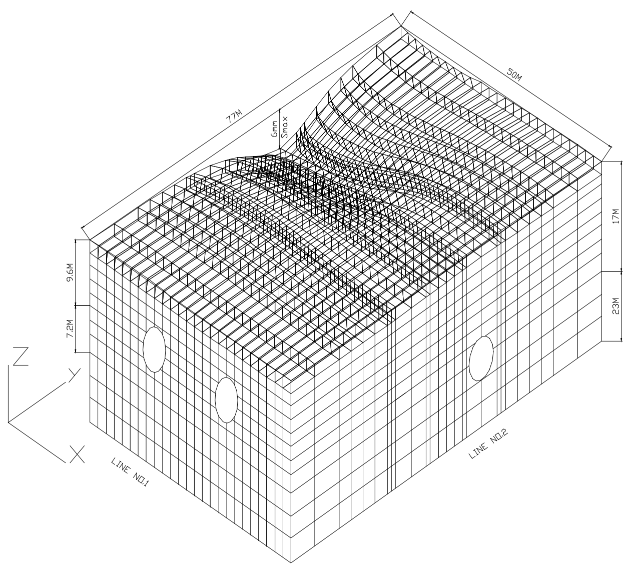

Figure 1. A case of shield tunneling ground settlement stimulated by 3-dimational finite element

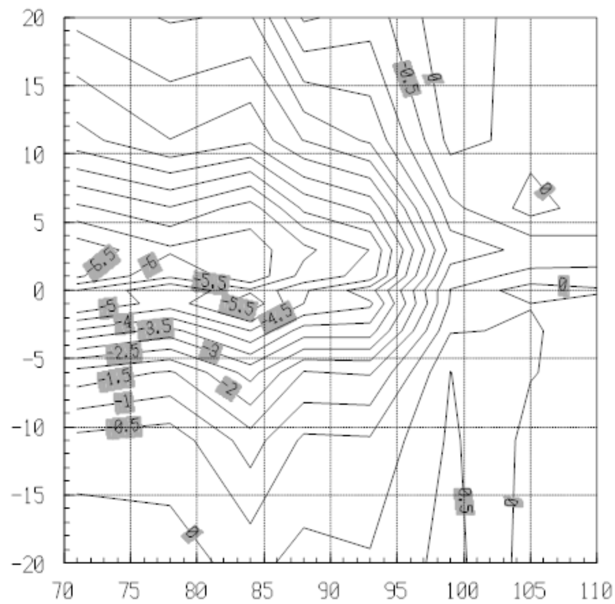

Figure 2. A case of soft ground settlement distribution of shield tunneling

2. Literature Review

2.1 Ground Settlement Induced by Formation Loss

Shield construction disturbs the corresponding soil mass during the process of tunneling, in which will lead to the formation loss caused by the soil mass loosing within a certain range [10]. According to the corresponding theoretical analysis and the summary of practical project examples, the factors causing the formation loss include the movement of the soil mass in the excavation face [11]. The soil mass could be squeezed into the gap of the shield tail. A change in the direction of travel and the front obstacles could make it difficult to fill in the gap caused by shield passage and causing formation loss [12]. The movement of the shield causes friction and shear to the stratum.Under the action of soil pressure, the lining of subway tunnel results in formation loss is caused by deformation.

2.2 Influence of Soil Thickness H and Outer Diameter D of Shield

Both the outer diameter of shield and the formation loss in per unit length affects shield construction [13]. The ground settlement caused by the shield driving occurs not only in the upper part of the tunnel axis, but also in various degrees in its surrounding area [14]. Theoretically,the ground settlement distributes in the Gauss curve in the cross-section of the tunnel axis. Under the same width of land settlement trough, the maximum settlement is usually in the middle.The larger the overburden thickness is, the smaller the maximum land settlement value will be, but the wider the land settlement trough will be.The maximum land subsidence decreases with the increase of the ratio of overburden thickness H to shield outer diameter D, i.e., H/D.

2.3 Ground Subsidence Caused by Groundwater

In the construction of deep buried tunnel, the ground settlement caused by formation loss mainly affects the end pile of the nearby buildings [15]. However, the decrease of groundwater level caused by groundwater loss mainly affects the shallow foundation of buildings and the length of friction piles.In particular, the formation with large clearance rate below pile foundation, such as medium coarse sand layer, which will result in large settlement [16]. In the process of earth-pressure balanced shield tunneling, the synchronous grouting of arch roof is generally not compacted enough, which leads to the hydraulic connection of arch roof along the direction of subway tunnel [17]. However, when the shield tunneling machine stops for a long time, groundwater tends to flow from the back of the shield tunneling machine to the excavation face, thus causing groundwater loss.When the local layer fluctuates greatly, or the stratum has the poor quality of geological drilling and sealing hole, it is easy to create the hydraulic channel with the upper stratum, which will lead to the decrease of groundwater level through the waterproof layer. In addition, in the stratum with large water content, the stop of the shield tunneling machine will also lead to the large water loss of the excavation surface.When the upper layer of the subway tunnel is covered with shallow and loose soil, and there are unblocked geological boreholes, the groundwater drops rapidly after the formation of a connected hydraulic channel. As a result, the surface subsidence is caused.

3. The Mathematical Expressions

To build a modern urban infrastructure, we first need to establish a modern urban comprehensive transportation system, which is mainly composed of Metro and mass rapid rail transit. At the same time, the construction of subway will promote the orderly evolution of urban morphology and the large-scale exploitation and utilization of underground space. The continuous construction of the subway and the development and utilization of the urban underground space are the inevitable trend and result of the sustainable urban development. Due to the small impact of construction process on the urban ground environment, shield tunneling is one of the main construction methods for subway and linear underground space facilities, such as common trench and traffic tunnel. Although compared with other construction methods, the stratum displacement caused by shield construction is relatively small, but it is always unavoidable. Therefore, the magnitude of stratum displacement caused by shield construction is one of the main requirements of control shield construction. Generally, soil deformation caused by shield tunneling are the main causes of the following aspects: stratum loss, formation of initial stress change, soil consolidation and soil creep, lining structure deformation, the soil displacement of a point in the field can be expressed as:

$$\delta=\delta_1+\delta_2+\delta_3+\delta_4+\delta_5$$

where:

δ: The total displacement of the soil.

δ_1: Formation displacements formed by formation loss.

δ_2: The displacement of this point caused by the change of the formation stress.

δ_3: Formation displacement formed by consolidation and creep of soil.

δ_4: The formation displacement caused by the deformation of the lining structure.

δ_5: The formation displacement caused by other factors.

The formation displacement of the so-called Loss of Ground refers to the displacement caused by the difference between the actual excavation volume and the volume of completed tunnel.The formation displacement caused by initial stress change means that in any surrounding rock medium, no matter how the tunnel is excavated, the result will inevitably lead to the change of initial stress and the stress redistribution and the corresponding strata movement.Ground displacement caused by soil consolidation and creep refers to: because of the squeezing effect of shield and shield tail grouting construction factors. The surrounding formation is coincided with the excess pore water pressure, and the excess pore water pressure in the tunnel construction will be a period of time after the dissipation of restoration, which will occur in the process of drainage consolidation deformation in the stratum.Formation displacement caused by the deformation of lining structure:The lining deformation mechanism of stratum displacement is caused by deformation of lining structure which will inevitably lead to the corresponding stratum loss. In general, the lining structure of stratum deformation caused by the deformation of the total displacement of strata were smaller, but when the tunnel lining structure deformation is large, the ground loss should not be ignored. The formation displacement caused by other factors: In addition to the above factors, water leakage often causes a decrease of segment surrounding soil pore water pressure, which leads to soil consolidation and ground displacement, the shrinkage grouting material during solidification, the new gap between the tunnel itself and the surrounding soil, which will also have the corresponding ground loss caused by ground movement.

4. Ground Settlement Induced by Shield Tunneling and the Related Factors

The magnitude of the depth and the curvature of the sinking and sinking curve is an important sign for the quality of shield construction. It is an important quality control standard for shield tunneling. For shield crossing nearby structures, it is one of important symbols to measure on neighboring structures through the influence of shield, such as shield ground deformation is small, can shield the disturbance of soil around the inevitable is very small, the effect on adjacent structures will be very small; conversely, if the shield the ground deformation is large, the influence of adjacent structures is large. The longitudinal and transverse settlement grooves in the shield propulsion have been studied in depth, but the shield propulsion is a dynamical continuous process. The longitudinal ground deformation of shield tunneling is shown in Figure 3. The mesh for finite elements longitudinal calculation model of shield tunnel is shown in Figure 4. The longitudinal stratum deformation in Shield Tunnel is shown in Figure 5.

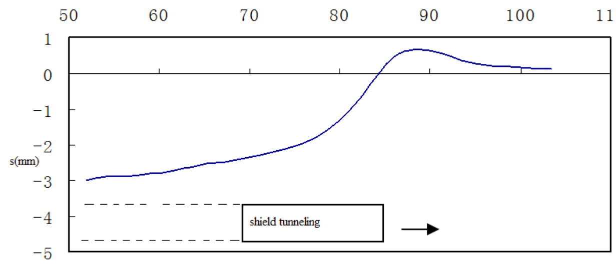

Figure 3. Longitudinal ground settlement induced shield tunneling

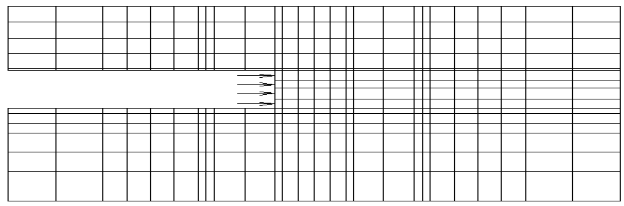

Figure 4. Mesh for finite elements longitudinal calculation model of shield tunneling

The mathematical model of the relationship between the ground surface uplift and the construction parameters of the shield is established. Mainly a lot, the construction parameters of surface heave effect of shield tunneling process: shield thrusting speeds, shield tail grouting quantity, control soil pressure, shield posture change of the thickness of the overlying soil extremely physical and mechanical properties, shield the incision and shield tail, head of shield cutter cutting soil cutter oil pressure and so on. In the case of small deformation, the relationship between these construction parameters and ground settlement can be assumed to be linear. The influence of each single construction factor on surface subsidence can be expressed as:

$$\{s_i\} = \{s_i \in w_i\}$$

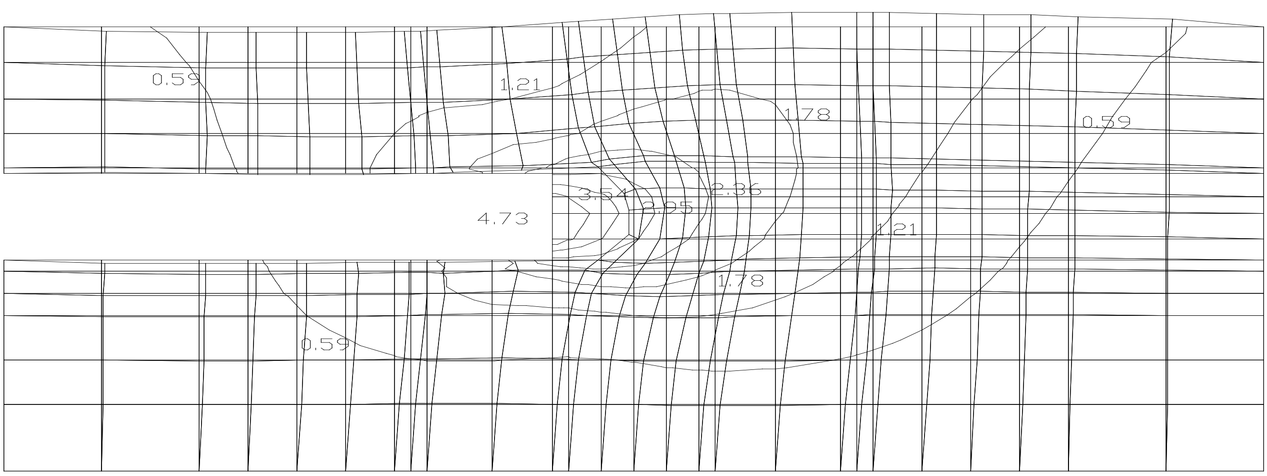

Figure 5. Longitudinal map of stratum deformation induced by shield tunneling

$$s_i = b_0(i) + b_i x_i$$

Where: $b_0(i)$is a fixed element corresponding to the w_i number field; w_i generated for the construction parameters of x_i heave number range; $x_i \in Q$, Q is total construction parameter space.

Therefore, $\{s_i\}$ is a linear manifold in w_i. In accordance with the principle of superposition. The relationship between the ground surface settlement and the construction parameters can be obtained in mathematical model as follows:

$$s = b_0 + \sum_{i=1}^{m} b_i x_i$$

Where：

$$b_0 = \sum_{i=1}^{m} b_0^{(i)}$$

b_0——Constant term.

$b_i(i=1,2\ldots\ldots m)$——Variable coefficient of construction parameters.

$x_i(i=1,2\ldots\ldots m)$——Construction parameters.

m——Number of parameters of construction parameters.

b_0, $b_1 \ldots b_m$ are determined by the method of regression analysis of the recorded values of the various construction parameters and the corresponding surface subsidence values.

5. A Practical Case on Ground Settlement Induced by Shield Tunneling

5.1 The Establishment and Analysis of Mathematical Model

According to the above analysis and a Shanghai shield field data in the process, based on the process of shield tunneling, shield synchronous grouting volume was $2m^3$/ring, speed of 3.0 cm/minute, therefore, the synchronous grouting volume and speed of the two construction factors can not consider the impact of surface subsidence, but can be set to the same in the two the construction parameters under the condition of other construction parameters on the influence of surface subsidence. In addition, the geological prospecting data along the tunnel are relatively rough, and the physical and mechanical properties of the soil can not be considered. This will also affect the results of the analysis to a certain extent, but generally it does not affect the general regularity. Therefore, the mathematical model of the surface settlement of the tunnel and the parameters of the shield construction can be simplified as follows:

$$S = b_0 + b_1 x_1 + b_2 x_2 + b_3 x_3 + b_4 x_4 + b_5 x_5 + b_6 x_6 + b_7 x_7$$

where：

s——ground surface settlement (mm).

b_0 ——Constant term.

b_1, b_2, b_3, b_4, b_5, b_6, b_7——Coefficients of construction parameters.

x_1——Frontal earth pressure of shield.

x_2——Thickness of overlying layer on shield.

x_3——Elevation difference of shield.

x_4——Adjustment of shield incision.

x_5——Shield tail height difference.

x_6——Shield tail adjustment.

x_7——Jack pressure of shield head.

5.2 Relation between Ground Surface Settlement and Shield Construction Parameters

According to the up 87 points and down 116 points measured data, by the corresponding construction parameters of the regression mathematical model of the above analysis, the relation between the ground surface settlement and shield construction parameters are as follows:

(1) The relationship between the maximum uplift of the surface and the construction parameters：

$s=29.2706-6.2203x_1-0.6729x_2- 0.0613x_3+0.0083x_4+0.0261x_5+0.0069x_6+0.0142x_7$

(2) The relationship between the final settlement of the surface and the construction parameters：

$s=-8.9765-3.0292x_1+0.3987x_2-0.0115x_3-0.0247x_4-0.0317x_5-0.0030x_6-0.0484x_7$

The following analysis is of the above two relations：

In the relation between the maximum uplift of the surface and the construction parameters, the constant term b_0=29.2706 is positive. Advance speed, positive soil pressure increasing process is usually the result of experience from the soft soil shield becomes hard is caused by the shield through soil deformation resistance from weak to strong, so in this process, the surface uplift degree decreases, so the coefficient of earth pressure b_1=-6.2203 positive construction parameters is negative; shield tunnel buried depth, with increasing thickness of overlying soil, the degree of impact on the surface will weaken the shield tunneling, the surface uplift caused by the corresponding amount will be reduced, so the influence of soil thickness on the shield coefficient b_2=-0.6729 is negative; the increase of height of shield incision over excavation quantity caused by the first part of the shield vertical direction increases, the vertical space will make a relatively large, weakened shield body corresponding to the overlying soil jacking upward extrusion pressure, which will make Reduce the amount of uplift of overlying soil shield, the notch coefficient b_3=-0.0613 difference is negative; due to shield the first swing around and around the upper and lower tail swing will increase and squeeze the soil around the disturbance, so that the uplift amount of overlying soil increases, so the shield incision adjustment, shield tail height with the adjustment of construction parameters influence coefficient b_4=0.0083, b_5=0.0261, b_6=0.0069 were positive; the first increase of shield cutter pressure will increase cutting force, cutter on the cutter cutting soil, expanding the scope of soil soil disturbance, make the surface uplift increases, so the influence coefficient of b_7=0.0142 cutter hydraulic construction parameters the positive.

The relationship between surface settlement and construction parameters in the formula; constant b_0=-8.9765 negative; increase when in the process of advancing front earth pressure, will expand the surrounding soil disturbance, thereby increasing the total settlement of shield tunneling across the ground after the soil pressure coefficient b_1=-3.0292 is positive is negative; when the shield the depth of the tunnel depth, with increasing thickness of overlying soil, the degree of impact on the surface will weaken the shield tunneling will reduce the surface subsidence caused by the corresponding amount, the influence of soil thickness on the shield coefficient b_2=0.3987 is positive; incision or increase shield attitude change of the shield tail will expand the surrounding soil and soil around the local over break with disturbance of the range and degree, so that the settlement of overlying soil increased, the shield incision and adjustment, tail height The coefficient of b_3=-0.0115, influence of construction parameters and adjustment of the height of b_4=-0.0247, b_5=-0.0317, b_6=-0.0030 were negative; increase the first shield cutter oil, will increase cutting force of cutter on the soil, expand the cutter cutting soil produced by soil disturbance, make the surface subsidence increases, the influence coefficient of b_7=-0.0484 knife the construction parameters for the negative pressure plate.

In conclusion, the relationship between surface uplift and settlement and construction parameters is reasonable, and the trend of construction parameters is correct when applied to engineering practice.

5.3 Comparison of the Calculation of Surface Uplift Formula with the Measured Curve

With the analysis of shield tunnel along the ground to promote the maximum heave and the final settlement of the two formula of Shanghai subway tunnel corresponding, and compared with the measured value engineering uplink and downlink line, the tunnel of the ground and the final settlement of the calculated and measured volume curve for the contrast, the maximum surface uplift calculation and measured and the change tendency of final settlement, the general trend is consistent. Because of data limitations, this paper analysis the model to the physical and mechanical properties of shield tail grouting, advance speed and experience along the formation of soil into account, inevitably there will be local values calculated by the individual measuring point is somewhat inconsistent with the measured values, but this apparently did not affect the general trend, it is enough to in this paper shows the calculation formula of two results is compared with the actual project, studied for settling law of long tunnel on the surface of the section, this research method is applicable.

6. Maximum Estimation of Ground Deformation in Shield Tunneling

According to the principle of optimization method and shield the maximum surface subsidence and uplift between the construction parameters, can be estimated under the condition of the maximum amount of heave is limited in some construction parameters, the maximum value of the essence of the problems is to find the objective function in certain variables under constraint conditions.

For the two relations of the surface sinking and sinking of shield driven interval tunnel studied in this paper, according to the geological condition of shield tunneling across the stratum, the construction quality requirement of the project itself and the condition of shield machine and equipment, the construction parameters should be limited.

$2<x_1<3$ (MPa)

$8<x_2<15$ (m)

$x_3<50$ (mm)

$x_4<50$ (mm)

$x_5<50$ (mm)

$x_6<50$ (mm)

$x_7<100$ (MPa)

It can be obtained that the maximum uplift $S_{max(uplift)}$ along the tunnel and the maximum settlement $S_{max(sink)}$ are as follows:

$S_{max(uplift)}$= 14.9318 (mm)

$S_{max(sink)}$= -23.2595 (mm)

Except for the unusual phenomena caused by the geological conditions in some areas, the maximum uplift of the surface is less than $S_{max(uplift)}$. In general, the maximum settlement is less than $S_{max(sink)}$, that is, the surface subsidence is generally between $S_{max(sink)}$ and

$S_{max(uplift)}$.

The comparison of the calculated and measured curves is shown in Figure 6. The variation trend of the maximum uplift and final settlement of the ground surface is very consistent with the measured data.

7. Conclusions

The contributions and research implications are the revealed relationships between the ground deformation and the shield tunneling parameters during construction, as is discussed in the mathematical model.

(1) In the design process of subway tunnel, the selection of lines must consider the impact on the tunnel roof and surrounding buildings if the tunnel settlement occurs. When using shield method for construction, it is necessary to fully consider the buildings on the ground and the weak ground floor, so as to avoid the buildings subsidence if they are unavoidable.If the tunnel construction is carried out along two lines, secondary settlement should be taken into account in different time periods. This factor should be fully considered in the design and, after relevant calculation, correct prediction should be made on the degree and harmfulness of surface deformation, and relevant data should be counted and recorded.

(2) As far as possible to reduce the impact on the formation, in the process of construction embodies in the following aspects: (a) The necessary preliminary inspection is the focus of the regional geological conditions, the basic conditions of groundwater, etc. (b) The continuity of construction and stable construction speed for advancing under the pressure of the earth and ensuring the surface subsidence control in the smallest range. (c) The excavated volume of the excavation face must be strictly controlled according to the successful experience of some projects. (d) A detailed survey of the construction operation surface in advance for keeping the shield on the design section and avoiding deflection as much as possible, so as to avoid the disturbance of soil layer generated during the rectification process.

(3) Filling and grouting for the building voids of the shield tail. (a) For ensuring the construction quality of the pipe piece and controlling the strength of the pipe piece, the waterproof layer and the lining pieces must be assembled tightly.Pressure injection work must be timely, shorten the exposure time for preventing collapse. (b) In consideration of shrinkage the grouting material, the injection volume must exceed the volume of theoretical shield tailing void space, generally more than 10% or so, or the grouting material should be mixed with expansion agent. Grouting pressure should be controlled as the standard of filling degree.When the pressure rises sharply, it indicates that the filling is compacted. At this point, the injection pressure should be stopped, and both the injection quantity and the grouting pressure should be taken into account.If the injection quantity has reached the specified standard and the pressure is very low, then the gap is large. In this case, the injection quantity should be increased until the pressure rises to the specified value. If the injection quantity is far in excess of the estimated shield tailing voids and the pressure is low, then the slurry loss should be treated according to the hydro geological data and actual investigation, such as sealing the watercourse and re-grouting.

(4) It was concluded that the shield construction parameters are of close relationship with the actual surface uplift or settlement. The optimization theory analysis method and the prediction are important for shield tunneling. Both theoretical research and the practical engineering analysis for shield tunneling should be aimed at the safety in the process of tunnel construction.

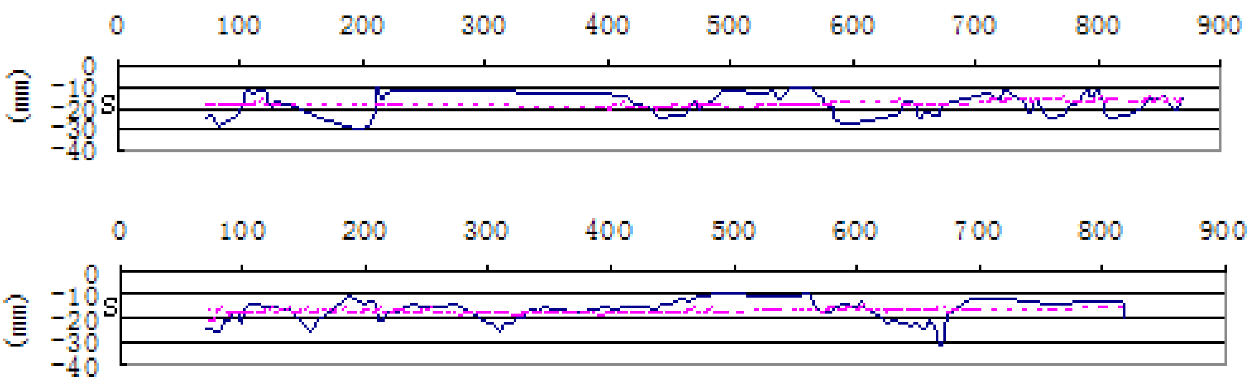

Figure 6. Two cases of ground deformation along with the longitudinal center of shield tunneling

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References

[1] Duan, S.T., September 2016. Surface settlement of subway shield tunnel construction. Traffic Construction. Vol.6, pp.261-262.

[2] Rajabi, A.M., Mahmoudi, M., Taebi, M., 2021. A Numerical Study of the Effect of Tunneling on Surface Settlement and Existing Buildings, International Journal of Engineering. Transactions B: Applications Vol. 34, No. 05, pp.1085-1093.

[3] Chen, I., Rabczuk, T., Bordas, S., Liu, G.R., Zeng, K.Y., Kefriden, P., 2012. Extended finite element method with edge-based strain smoothing (esm-xfem) for linear elastic crack growth. Computer Methods in Applied Mechanics and Engineering. Vol. 209, 250-265.
DOI: https://doi.org/10.1016/j.cma.2011.08.013.

[4] Chen, R., Zhang, P., Wu, H., Wang, Zh., Zhong, Zh., 2019. Prediction of shield tunneling-induced ground settlement using machine learning techniques. Frontiers of Structural and Civil Engineering. Vol. 13, 1363-1378.
DOI: https://doi.org/10.1007/s11709-019-0561-3.

[5] Zhuang, X., Zhou, S., Sheng, M., Li, G., 2020. On the hydraulic fracturing in naturally-layered porous media using the phase field method. Engineering Geology. Vol. 266.
DOI: https://doi.org/10.1016/j.enggeo.2019. 105306

[6] Zhou, F., Molinari, J.F., 2004. Dynamic crack propagation with cohesive elements: a methodology to address mesh dependence. International Journal of Numerical Methods in Engineering. Vol. 59, No.1, 1-24.
DOI: https://doi.org/10.1002/nme.857.

[7] Rabczuk, T., Belytschko,T., 2004. Cracking particles: a simplified meshfree method for arbitrary evolving cracks International Journal of Numerical Methods in Engineering. Vol. 61, No. 13, 2316-2343.
DOI: https://doi.org/10.1002/nme.1151.

[8] Qiu, J.S., July 2010. Analysis of ground settlement in shield tunneling of Subway. Green and environment-friendly building materials. pp. 128-129.

[9] Hu, J.M., 2020. Research on the Key Points of shield Tunneling technology in Subway. Engineering Construction. 2020(1), pp.246.

[10] Zhang, Z.K., June 2000. Study on Ground Settlement of Shied Tunneling. Postdoctoral Research Report. Tong Ji University.

[11] Zhang, Z., 2013. A review on the long-term settlement of shield tunnel structures. Engineering construction. 2013(3), pp.135-140.

[12] Yan, Z.G., Fu, Y.C., Du, L.F., June 2012. Study on surface subsidence of shield tunnel. Journal of Shijiazhuang Institute of Railway Technology. pp.4-8.

[13] Ding, C., May 2020. Analysis and Control Measures of Surface Settlement during Shield Construction in Soft Ground. Value Engineering. pp.169-170.

[14] Tang, Y.Q., Ye, W.M., Huang, Y., October, 2000. Prediction of Ground Settlement Caused by Subway Tunnel Construction in Shanghai. Proceedings of International Symposium of Civil Engineering in 21st Century, Beijing, China. pp.439-443,11-13.

[15] Cai, Q.G., Li, J.M., Sun, J., 2020. Influence on Subway Shield Tunnel by Short — distance Pile Foundation Construction in Soft Soil and Sand Layer Area and Its Treatment. Survey science and technology. 2020(3), pp.28-31.

[16] Zhang, B., July 2020. Ground settlement control of shield tunneling in water-rich sand layer. Traffic Construction. pp.274-276.

[17] Shang, S.D. 2020. Research on a new type of grouting technology for shield tunneling which can effectively control land subsidence. Road engineering and Bridges. 2020(1), pp.117-118.