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Shield tunneling and environment protection in Shanghai soft ground

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ABSTRACT

Large scale and intensive metro construction through dense urban area increases sharply the impaction on risk control and environment protection. Three typical cases of shield crossing building above ground (SCBA), shield crossing tunnel from above (SCTA) and shield crossing tunnel from below (SCTB) are studied, respectively, based on field measurements and site investigations of actual projects in Shanghai soft ground. The risks of shield crossing sensitive buildings and subways, ground movement prediction and its control regulations, the settings of shield driving parameters such as earth pressure, driving speed, postures and grouting are demonstrated and summarized in detail. It is proposed that stringent stipulations on controlling ground volume loss (GVL) ratio (GVLR) and strengthened monitoring measures are necessary and substantial for eliminating/reducing potential construction risks. It is urgently decisive to improve the performance of shield machine and to make it more flexible for counteracting complications of geology and environment, as refer to the present status of shields in Shanghai, most of them being overused or out of date.

1. Background

With rapid development of Shanghai, the accelerated urbanization has made the development and utilization of land as well as underground space become the very important factor affecting the sustainable development of urban society. Since 30 years of open policy, huge urban railway transport systems have been planned in such cities as Beijing, Shanghai, Guangzhou, serving as 3D frame of underground space utilization, and now the ambitious plan is being put into construction at ever highest speed. As for Shanghai, eight metro lines with total length of 230 km have been completed within past 20 years. By 2010 before Shanghai EXPO, 11 metro lines with total length of 400 km will be in operation in which 9 lines run through urban central areas and most of them are tunnels constructed by shield machines. Meanwhile, a total number of 14 large scale vehicle tunnels crossing Huangpu River have been planned in which 8 tunnels have been completed and 6 tunnels being under construction. Most of them are/will be built by shield machines.

The shield tunneling technology has developed quickly and used widely these years to meet the demands of large scale tunneling projects and has achieved good results featuring high speed, safety, small disturbance to ground surface. But with a large number of tunnels driving closely across buildings and running subways, intensive and difficult construction has produced unforeseen risks and potential problems. More and more frequently the high sensitive and unstable ground have been/will be met which results in sharp increasing risks and heavy impaction on environment. The settlement allowed for these closely located facilities are usually a few millimeters. Although normal techniques and experiences from past two decades could guarantee the ground settlement to be controlled within (−10 to 30) mm, they are now becoming no longer so feasible and practicable in Shanghai. It is in urgent need that an effective way of controlling shield driving be developed and studied.

The typical Shanghai soft ground is composed of littoral deposits featuring with saturated, flow to soft plastic clay with high compressibility and sensitivity and low strength, long stabilizing time and big settlement after being disturbed. In order to counteract the difficulties from geological condition, advanced shields have been developed in both domestic and abroad. The ground volume loss ratio (GVLR) by disturbance of shield has been minimized to about 5‰ by application of advanced shield and relevant construction techniques in developed countries of the world (Mair and Taylor, 1998; van Hasselt et al., 1999). While in Shanghai, the GVLR has been controlled within 1% under normal conditions. With the development of Shanghai metro network, the frequency of close crossing below/above running subways and nearby residential buildings will be increased a lot and lead to a huge surge in risks. In very complicated geology and environment, the GVLR produced by shield has been controlled within 1–5‰ in order to protect the sensitive residential buildings and to ensure the safety operation of running subway tunnel by taking very special

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Table 1
Relevant research methodology for prediction of ground movement induced by shield.

Theoretical study methods	Laboratory test	Field test
(1) Classical mathematics and mechanics (2) Modern mathematics (grey system, fuzzy and neuro-net) (3) Numerical modeling (4) Empirical method	(1) Soil behavior under small disturbance (2) Large scaled or prototype model test (3) Small scaled similarity model test	(1) General construction monitoring (2) Automatic or remote controlled monitoring (3) Feed back analysis

measures. It has been realized in common that stringent regulation on GVLR not only forces the construction contractors to strengthen their administration but also the performance of shield equipments, and consequently leads to elimination/reduction of various risks and to satisfy the requirements of environment protection in spite of changing conditions.

Three challenging projects, very typical cases in study, of which two are the shield crossing running tunnel from above (case SCTA)/ or from below (case SCTB) with only about 1 m space, the third one is the shield crossing 8 m under the seriously inclined old residential Buildings (case STBA) in Shanghai, have been commenced successfully with a so called technology "small disturbance construction" (SDC) (Liao et al., 2006) and all around control method, which will be described in latter sections.

Since 1960s, both domestic and abroad scholars have made a large amount of research on the settlement prediction due to shield tunneling. And the research methodology can be summarized in Table 1:

The basic status of relevant research achievements on ground movement prediction are demonstrated as following:

(1) The settlement trough of Gaussian distribution curve proposed by Peck (1969) is based on the concept of ground volume loss (GVL) and widely accepted by engineers in settlement prediction due to shield tunneling. Favorable results has achieved by applying the method in homogeneous and saturated soft ground (Liu and Hou, 1991).
(2) A lot of scholars and experts have applied 2D/3D FEM to model the ground movement induced by shield tunneling with elastic, elasto–plastic and visco–elastic constitutive models of ground stratum (Akagi and Komiya, 1996; Sugimotol and Sramoon, 2002; Komiya et al., 1999). These approaches have been proved on their validity in solving complicated engineering problems under certain assumptions on ground properties, GVLR and construction parameters (Chen, 2008; Liao and Yang, 2004; Liao et al., 2007).
(3) Small disturbance experiment on soil behavior (Liao and Yang, 2004), centrifuge model test (Toshi Nomoto et al., 1999) and high precise of site measurement on ground movement, have been accepted in more common by engineers and played a more and more important and constructive role in Shanghai tunnel engineering.

2. Prediction of settlement and its effect on environment

To ensure the safety of environment in close proximity to shield tunnel, the theoretical prediction jointed with experiences on ground movement should be done before construction. In the prediction, GVLR and correspondent construction parameters of shield should be assumed in order to guarantee the predicted ground movement be within allowable limits of adjacent buildings and facilities under the assumed conditions. The study made below combining both domestic and abroad achievements with Shanghai metro tunneling practice focuses on the special ways of solving problems in crossing old buildings and running subway tunnels in Shanghai soft ground.

In settlement prediction, 3D numerical modeling with Elasto–Plastic constitutive law and Drucker–Prager criterion is applied. The ground volume loss is simulated with equivalent gap parameters and the grouting process is simulated by volume expansion elements. The segmental tunnel lining is simulated with shell element with equivalent stiffness regarding the joint effect (Liao et al., 2008a).

2.1. Settlement Prediction for case SCBA

2.1.1. Prediction and monitoring requirements

It is common sense that detail environment investigations include two parts: the first is about the building, its relative location and initial status as well as geological conditions, and the second is the near surroundings of the building, such as underground structures, obstacles, pipelines, especially the important /or dangerous pipes (gas pipes). The two parts form the integrity of boundary conditions which imply not only the adding of control items but also their interactions. It should be stressed and clarified here that complication lies in the interaction between the two parts in the control implementation due to their different response to the shield tunneling.

In the project example here, the residential building is five-storey masonry structure, built in 50 years ago, and has inclined for 1.7% before construction as seen in Fig. 1. The external walls have been severely weathered. Apparent aging effects on buildings have been observed on the internal load bearing walls and beams. In addition, there are two pipelines (D300 gas pipe and D300 water supply pipe) situated closely along the building foundation edge at the side of tunnel.

Three-dimensional modeling is applied in the ground movement prediction (Fig. 2) and the material properties applied in the model are listed in Table 2. The stiffness of the building is ignored but the initial stress produced by self-weight (100 kPa) of the building in ground is introduced by initial analysis. The structure elements are considered ideal elastic and the ground is regarded as elasto–plastic with Drucker–Prager criterion applied.

GVLRs of 1‰, 3‰, 5‰ and 10‰ are assumed, respectively, to modeling different construction conditions. The maximum settlement and inclination of buildings can be obtained from analysis results as seen in Fig. 3. By safety assessment and critical analysis on the building, the additional allowable inclination of 3.5‰ is obtained. Based on the above prediction and assessment, the allowable GVLR, the maximum settlement of building and inclination of load bearing walls is determined as 5‰, 10 mm, 3.5‰, respectively. Field measurement results show that the settlement of building is in good accordance with the predicted under the assumed parameters (Fig. 4).

2.1.2. Pressure settings and settlement

It has been foreseen that the earth pressure at shield workface will be changing due to the variation of ground and environment conditions. The 3D FEM analysis on the effect of pressure on settlement of buildings had been conducted. The analysis results show that when the deviation of supporting earth pressure to that at rest is bigger than 0.04 MPa, such a favorable results can be achieved

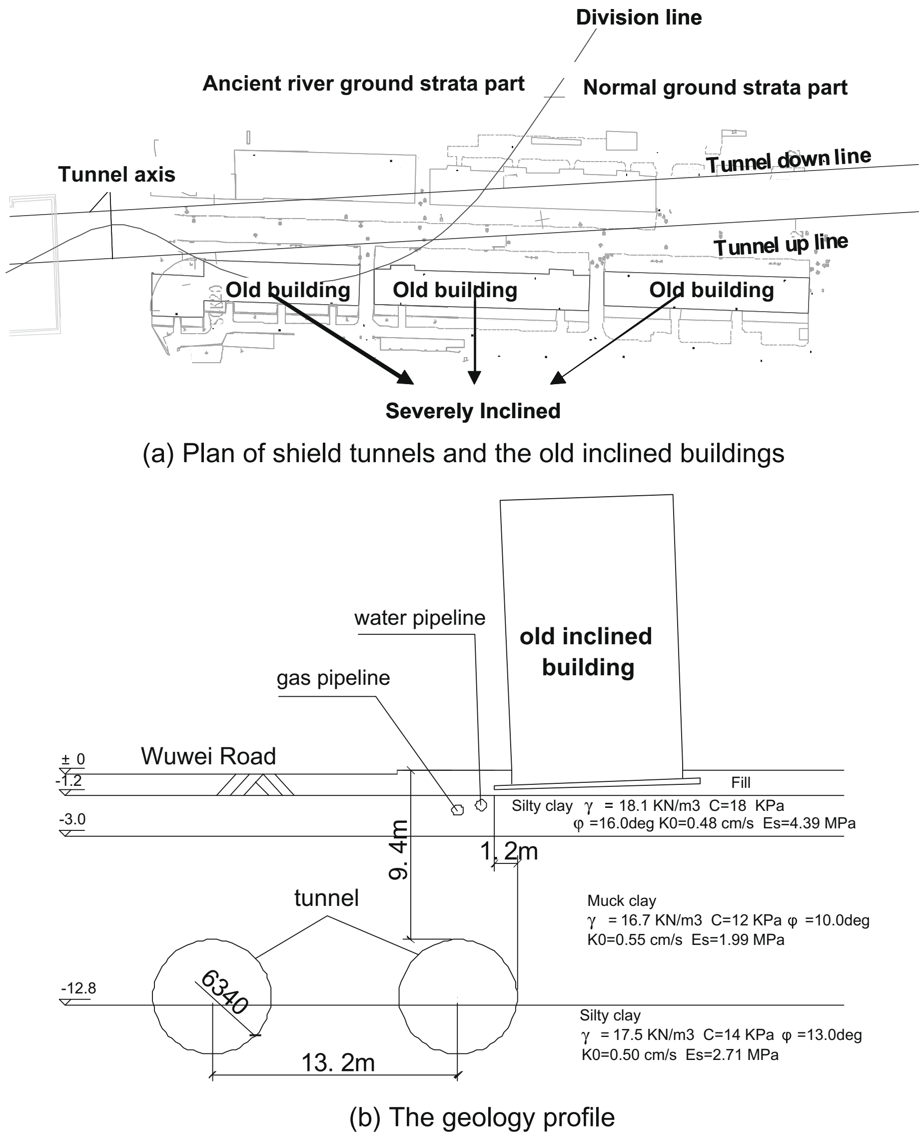

Fig. 1. The adjacent conditions of the old inclined building (from Liao, Chen and Shen 2007).

that the settlement of building and the heave of pipeline will be both controlled within small values (see Fig. 5). The pressure deviation in the earth cabinet is governed by the sensitivity of shield control system and relevant equipment performance relying on the shield manufacturers.

2.1.3. Positioning of grouting holes and settlement

Before grouting implemented from tunnel, numerical modeling was conducted on the effect of grouting at different positions in order to choose the best grouting holes. There are totally 16 embedded grouting holes per ring in which holes No. 7–16 on the left side are excluded due to their apparent disadvantages. Only holes No. 1–6 on the right side near the building are selected for analysis and comparison. The squeezing effect of grouting is simulated by volume expansion element, of which the expansion ratio is determined according to the grouting volume and void ratio of ground stratum as well as grouts properties. The modeling results show that only two grouting positions of the total 15 holes are available which can minimize the settlement of building and prevent over-heave of adjacent gas pipelines in the meantime (Fig. 6).

Numerical modeling results also show that grouting from hole 1# or 2# brings about apparent settlement to the building and heave to the adjacent gas pipeline, grouting from hole 3# or 6# causes both the building and pipelines to settle, grouting from hole 4# or 5# causes the building to heave and little effect on pipelines. It is clear now that the grouting effect of holes 4# and 5# are the best and that of holes 1#, 2#, 3# and 6# is unfavorable. The field measured displacement of building and adjacent pipe due to different

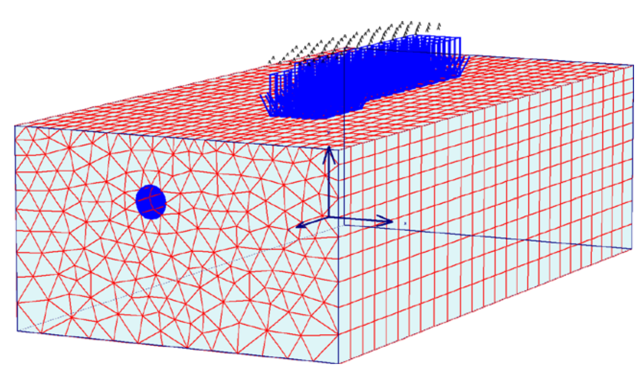

Fig. 2. The computation model (case SCBA).

Table 2
Material properties in the model.

Type	Density (kN/m^3)	Earth pressure coefficient at rest	Young's modulus (kPa)	Poisson ratio	Cohesion (kPa)	Friction angle (deg.)
Ground	18	0.7	5000	0.4	15	10
Foundation	25	–	3E7	0.2		
Lining concrete	25	–	3E7	0.2		

grouting holes (Fig. 7) provides the facts verifying the above numerical modeling deductions. Grouting from hole 4# induced incremental heave of building about 0.5 mm and 0.25 mm of pipe which matches the calculated values to some extent.

However, numerical modeling can only provide conceptual recommendations for the reason that it is impossible to make an accurate simulation on grouting, a very complicated mechanical process involving material chemical reactions. Nevertheless, field measurements proved that the modeling could supply favorable guidance for setting key parameters such as grouting pipe length and pipe locations which produce much difference in high sensitive soft ground.

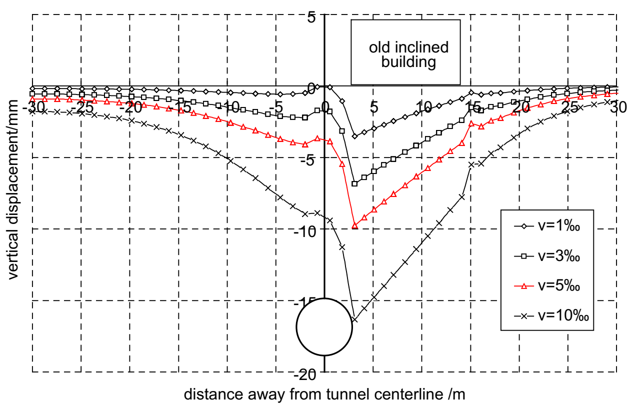

Fig. 3. The surface settlement through with different GVLR (case SCBA).

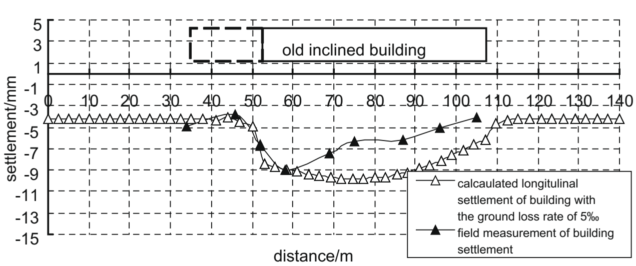

Fig. 4. The comparison between computation and filed measurement (case SCBA).

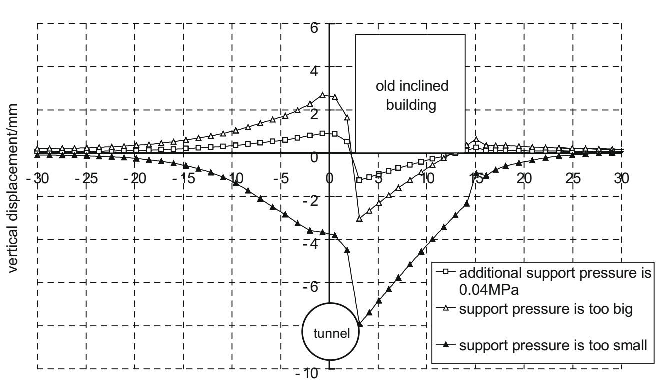

Fig. 5. Building settlement induced by various support pressures (case SCBA) (a) grouting position and pipe length (b) grouting results of different pipe locations.

2.2. Heave prediction for case SCTA

2.2.1. Heave prediction and monitoring requirements

According to tunneling experiences of Shanghai, sharp heave produced not only from the stress release due to shield driving, but also from the "weight reduced effect" (Liao et al., 2005) of the above tunnel in case SCTA. For instance, in a project of Shanghai, a shield of metro line 8 was driven across only 1.4 m above the metro line 2 which is the busiest and crowded line in operation. Numerical modeling was carefully conducted to predict the heave of the metro tunnel and to assess risks for acquiring technical specifications before construction (Fig. 8). Ground stratum was assumed as Elasto–Plastic and Drucker–Prager criterion was applied in the numerical model. The ground properties are listed in Table 3 (Cao and Yao, 2005).

In order to consider the effect of tunnel stiffness with joints, the elastic modulus (Ec) of lining concrete is modified according to the equivalent bending stiffness $(EI)eq$ of segmental lining in which the inertia of lining section and poisson ratio of concrete remain unchanged while the modulus is reduced from 3.57×10^7 kPa to 1.67×10^6 kPa. Two states were selected for the analysis as following:

(1) Normal state: GVLR is taken as 1% (the up bound of shield control level in Shanghai) and the corresponding stress release ratio is $\lambda = 0.3$ during shield passing.
(2) Ideal state: The GVLR and the corresponding stress release ratio are both taken as zero during shield passing. That means the heave of subway tunnel may be caused completely by stress release after shield passing (weight reduced effect of tunnel).

The settlement of running subway tunnel is 3.9 mm and 2.1 mm, respectively, under the above two critical states by the numerical modeling. Considering the superposition of the twice crossing by shields and uncertainties of geological condition, the total settlement will be bigger than 5 mm which needs to be reduced more to ensure the absolute safety of subway.

The final control objective of GVLR is determined as 5‰. To check the validity of the backup measures, the sensitivity analysis on the factors affecting heave has been conducted and an appropriate magnitude of ballast is designed to sustain the heave of tunnel.

2.2.2. Execution and results

To meet the stringent requirement on GVLR of 5‰, the experimental tunneling had to be conducted to optimize the construction parameters to achieve the goal of heave of 3.1 mm. The control results from experimental tunneling data had been proved to be basically in accordance with the numerical prediction. When the optimized parameters (Table 4) were applied in the construction process of crossing, the final heave of subway tunnel is a little big-

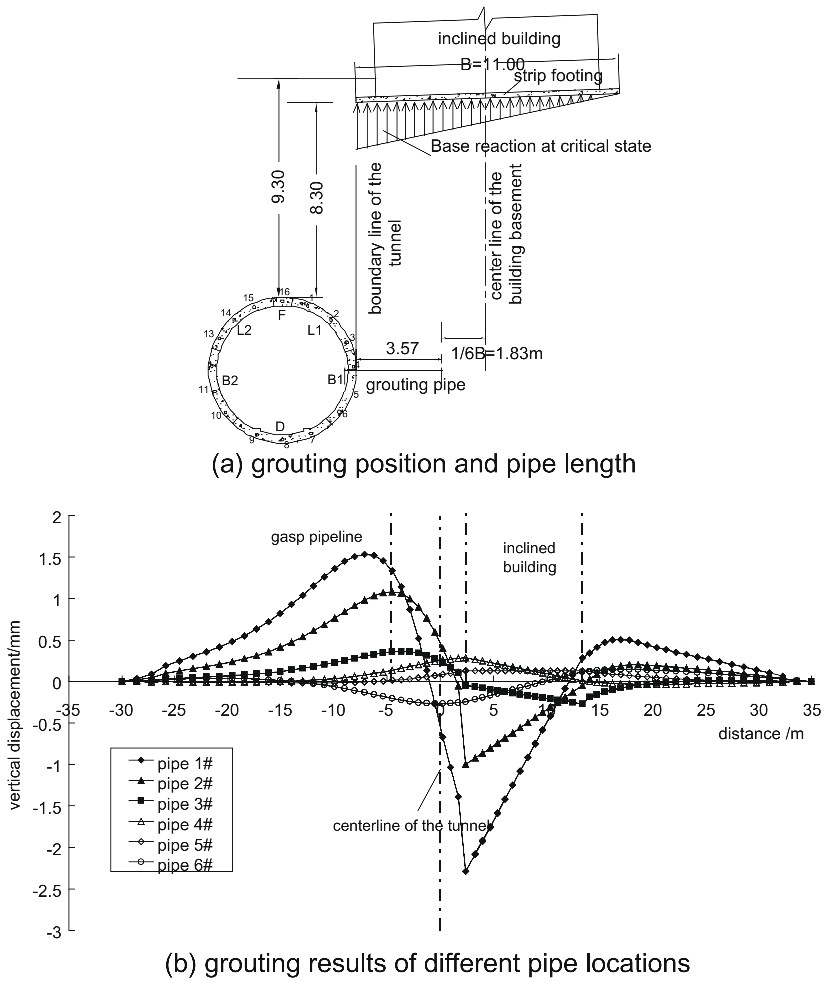

Fig. 6. Pipe length and grouting effect of each pipe (case SCBA, from Liao and Yang, 2004; Chen, 2008).

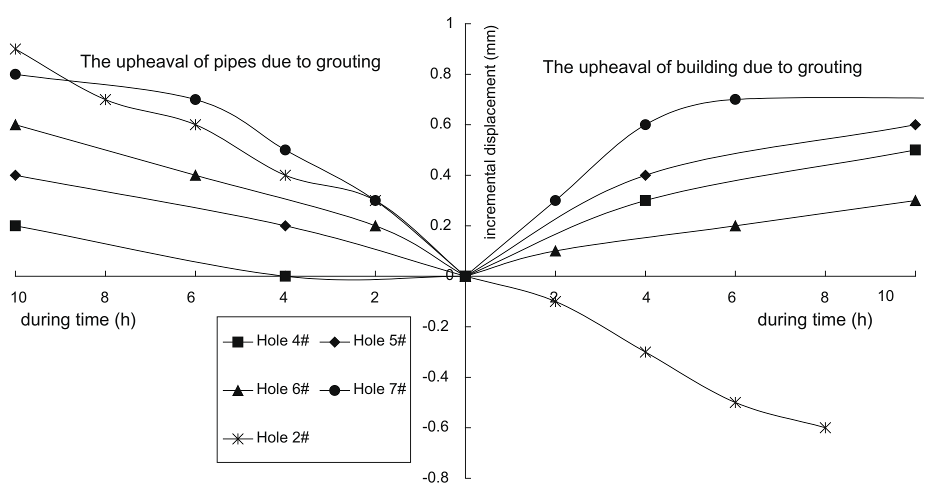

Fig. 7. Field measured displacement of building and pipe due to grouting from different holes.

ger than that of the summation of the twice crossings of two shields (see Fig. 9).

This may be caused by the secondary disturbance induced by the double crossings of shield, i.e. the second time crossing had being constructed in disturbed ground by the first time crossing.

In order to stabilize and reduce the heave of running tunnel at below, an average 2.5 tons/m ballast of steel sand had been applied in the tunnel along the 20 m long crossing part. In addition, the segmental rings within the crossing area are connected with steel channels to strengthen the longitudinal stiffness of tunnel to

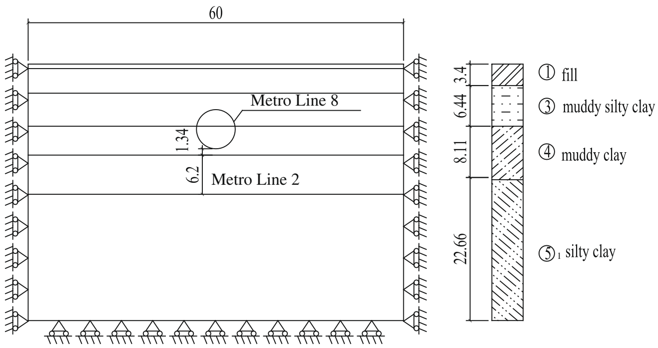

Fig. 8. Computation model (case SCTA) (unit: m).

Table 3
Ground stratum properties applied in the computation model.

Soil layer	Modulus (kPa)	Poisson ratio	Cohesion (kPa)	Friction angle (deg.)
Fill	4000	0.4	20	18
Muddy silty clay	3350	0.42	16	15
Muddy clay	2410	0.43	14	15
Silty clay	3820	0.42	16	17

From Cao and Yao, 2005.

Table 4
Optimized driving parameters.

Earth pressure (MPa)	Driving speed (mm/day)	Grouting volume (m^3/ring)
0.23–0.25	<10	2.8–3.4

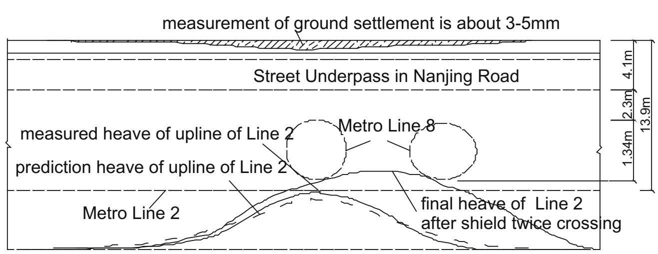

Fig. 9. The tunnel heave and surface settlement caused by shield crossing on the above (case SCTA).

prevent loosening of joints and water leakage. The final results verified that the measures taken are effective and the controlling objective set for the construction be reasonable and feasible.

2.3. Settlement prediction for case SCTB

2.3.1. Settlement prediction and monitoring requirements

In case of shield crossing subway tunnel from below (SCTB), settlement of the above tunnel will probably be induced by insufficient support at workface or/and grouting at shield tail. The shield control strategy should be based on the displacement prediction and in accordance with the safety requirements of subway running, as listed in Table 5.

Most subway tunnels close to tunneling projects under construction are located in saturated clay of high compressibility and sensitivity (St = 6–8) and a very small space of 1–2 m near from shield in construction. To reach the goal of displacement control and to clarify the construction requirements, 3D FEM and PECK formula have both been applied in detail analysis for comparison on the impaction of every risk aspects under various assumed GVLRs.

Table 5
Allowable deformation of Shanghai subway tunnel in operation.

Requirements for safety operation of subway	Requirements for structural deformation
Differential settlement between two tracks: 2 mm (i.e. transverse inclination: 1.4‰) Longitudinal differential settlement along rails: 4 mm/10 m	Longitudinal deformation of tunnel lining: ±5 mm Horizontal deformation of tunnel lining: ±5 mm Diameter convergence: 20 mm

The predicted volume of settlement trough by PECK is less than that by numerical modeling without consideration of the effect of the stiffness of tunnel lining, but a lot of engineering practices prove that the predicted value by PECK is relatively closer to the field measurement in comparison. So, the allowable GVLR is determined according to PECK formula in case of shield crossing below running tunnel for sake of safety in soft clay.

The volume of settlement trough at the bottom level of tunnel with maximum settlement of 5 mm is taken as the allowable GVL. The ground surface settlement allowed is deduced according to the above GVL and leveling effect of ground (Fig. 10).

Both settlements at depth of tunnel invert and above ground are taken as monitoring items for optimizing shield driving parameters before entering the area right below subway tunnels. After that, the shield driving parameters will be fine tuned according to the variation of the automatic electronic leveling instrument installed on the tracks. However, the parameter of earth pressure should be fatherly modified by considering the effect of tunnel lining overhead. All those projects in Shanghai based on the above principles have achieved favorable results until present.

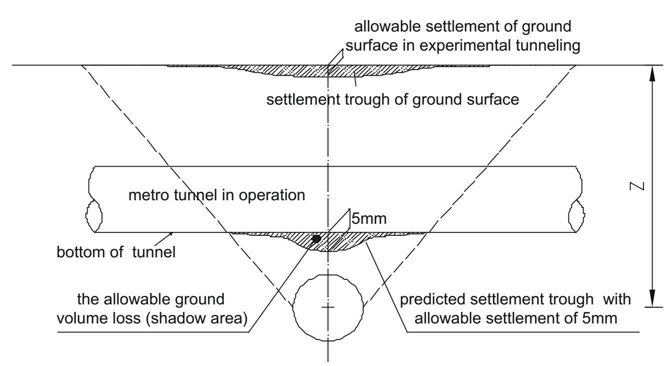

Fig. 10. The settlement estimation and monitoring of shield crossing below running subway (case SCTB).

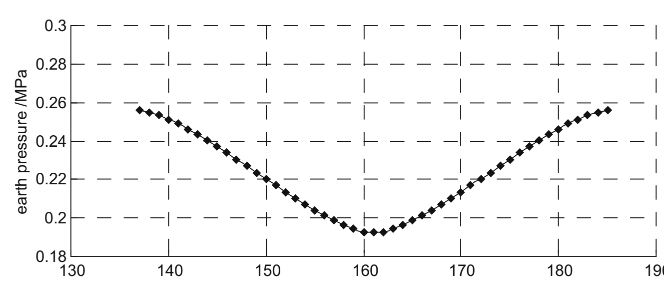

Fig. 11. The predicted earth pressure below subway tunnel line 2 (case SCTB, from Liao and Yang, 2004).

2.3.2. The earth pressure prediction

In case SCTB, the calculation considering the effect of unloading and bearing effect produced by the above tunnel was conducted to achieve more accurately the pressure acting on the work face (Fig. 11). As seen in Fig. 11, the very special distribution of the earth pressure was obtained by calculation which indicates that the earth pressure in the shield earth cabinet should be set in such a way that the pressure drops down slowly as shield passing beneath the tunnel and increases gradually after shield leaves.

3. Requirements on field measurement

To ensure the safety of running subway and residential building as well as adjacent infrastructures, the automatization and frequency of monitoring should be strengthened and increased to guarantee the feed back speed and accuracy of field measured data. Only by this way, the all around and the entire time control concept on GVL could be implemented.

3.1. Measurement requirements

The measurement accuracy and frequency should be determined according to the prediction results of settlement and the allowable value of protected objects as well as the GVLR requirement. As to the very stringent requirements of environment for construction, the automatic monitoring measures are usually required to realize the real-time monitoring in order that the construction parameters can be optimized and adjusted in time to control GVL.

3.1.1. Requirements for case SCTA/SCTB

The movement of subway tunnel should be strictly limited within ±3 mm (i.e. 2/3 of the allowable value) and the manual measurement is prohibited during metro operation. So the highest level of requirements is proposed for shield construction passing through running metro tunnel in close proximity. To ensure the absolute safety of running subways, the automatic measurement is adopted. The fixed type electronic leveling of high accuracy (0.1 mm) are instrumented near the middle of track bed which can be remotely controlled and its dada acquisition frequency of generating a set of continuous monitoring data of subway tunnel settlement every 5 min can be achieved. Deliberate control is necessary on support pressure at workface, grouting volume and pressure which are very sensitive to movement of nearby subways. The high accuracy leveling for measurement of horizontal movement is conducted during the stoppage of trains at nights. In case of general conditions, the horizontal movement of tunnel is usually very small in comparison with the vertical movement, so only the leveling for settlement is enough for monitoring to guarantee the operation safety of subway tunnel to some extent.

3.1.2. Requirements for SCBA

Generally speaking, automatic and high frequency of monitoring is necessary for strict environment protection. Besides measurement on buildings, measurement on the pipelines including water supply and gas pipes surrounding the building is indeed necessary because of their quite different responses to displacement and mitigating measures. In the example of case SCBA aforementioned, the automatic leveling had not been installed due to the anxiety on the panic of residents from their ignorance about the facts of the engineering. The manual measurement had been applied and the accuracy of leveling instrument is required on 0.2–0.3 mm according to the technical specification. To meet the high requirement for adjustment frequency of shield parameters during crossing, the monitoring is required for once an hour under normal condition and once every 5 min in case the data is unstable or vary sharply.

Manual monitoring produces intensive task and demands large amount of surveyors at site who should stand still for long time keeping the stick gauge and reading the instrument every 5 min. It is really a hard work for the site engineers to work at such a frequency; however, manual monitoring arrives at such a result as nearly real time monitoring.

3.2. Shield type and control conception

To meet the requirements for accurate feed back control, EPB (earth pressure balance shield) type shields used in closing projects are required to equipped with comprehensive, reliable, high precise sensors and monitors to display key control parameters such as earth pressure, grouting pressure and volume, postures etc. These sensors should work stable in case of difficult ground and shield under peak operation for long. In addition, high reliability to resist water and grouting pressure of tail brush should be guaranteed. In case of tunneling in sharp curvature, AEPB shield (articulated EPB equipped with the articulated joint between the forward shield and tail shield that allows angular movement between the shields) should be used for reducing additional ground loss induced by direction correction in curvature. DOT (double O tube, an EPB type shield with two spoke cutter wheels of the shield rotating in the opposite directions on the same plane) type shield produced much larger ground movement than the one tube EPB in tunneling practices of Shanghai for its difficulty in rolling control and insufficient support of workface due to its large opening ratio. Therefore, DOT type shield can be used tentatively only after being carefully checked and renovated SPBS (Slurry Pressure Balance Shield) type shield is not recommended for close tunneling in sandy ground for the high risk of bursting of pressurized slurry into neighbour tunnel.

The deformation mechanism by shield close tunneling has been recognized according to the ground movement features at different parts around shield (regions from part 1 to part 5 in Fig. 12). The control items relevant to shield driving in case of crossing subways can be obtained according to their respective effects on deformation as seen in Fig. 13. It can be concluded from Figs. 12 and 13 that the ground movement can be completely put under control by taking countermeasures for different parts of shield body.

In Fig. 12, the part number 1–5 represent five different factors, respectively, affecting ground movement as demonstrated in the following:

1. Ground movement induced by unbalanced support pressure/or collapse of workface.
2. Ground deformation caused by shield friction between shield shell and ground.
3. Ground settlement induced by GVL caused by changes of shield postures.

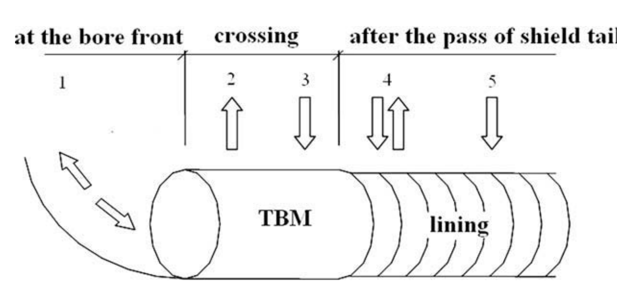

Fig. 12. The mechanism of deformation induced by shield driving (Liao and Yang, 2004).

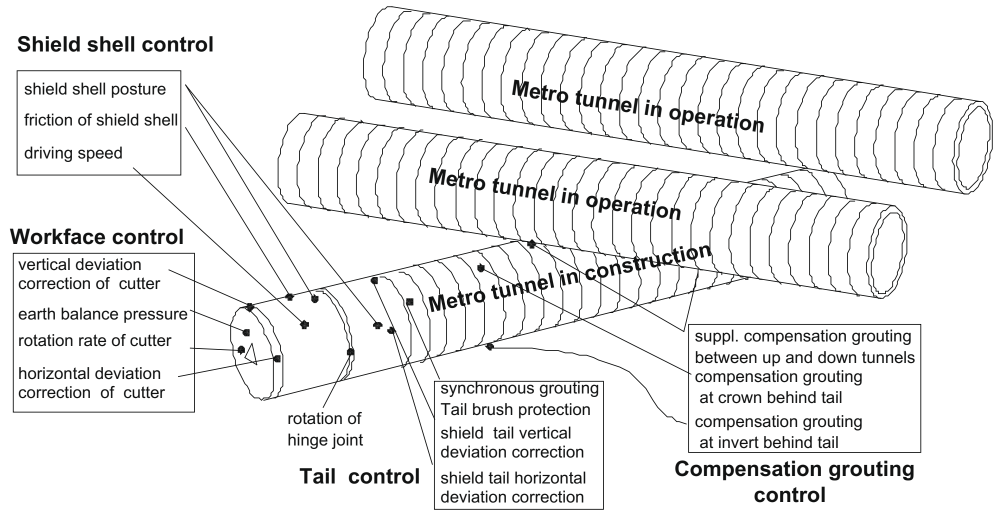

Fig. 13. Shield disturbance control strategy in close tunneling through subway (case SCTB).

4. Ground displacement induced by shield tail gap and synchronous grouting during shield driving.
5. Ground consolidation and creep induced by joint effect of the above four factors of disturbance.

The counteracting measures with regard to the all above factors at different parts of shield are listed below:

(1) Workface: fine settings and tuning of earth pressure, jacking speed, cutter head corrections.
(2) Shield shell: Backpressure grouting, friction reduction slurry injection, hinge connection.
(3) Shield tail: synchronous grouting, tail brush protection, leakage prevention, grease injection.
(4) Segment grouting: at crown and invert of tunnel, compensation grouting.

The control method oriented to mitigate the impactions of above 5 factors is called all around control method (Liao and Yang, 2004).

3.3. Optimization and adjustment of shield parameters

3.3.1. Earth pressure prediction and control

The support pressure is the first key parameter for shield driving. Generally, the magnitude of support pressure at work face is determined according to the earth pressure at rest of ground in case of no surcharge above ground. But the ground earth pressure is changing constantly due to the variation of geological conditions and turbulence of shield machine itself. The deviation of the set value by calculation to the actual is inevitable and thus needed to be optimized by experimental tunneling to achieve minimum ground movement (heave/settlement). The key points of measurement on building are chosen as the monitoring point for feed back control according to the response analysis of building. Fig. 14 depicts the variation of earth pressure of case SCBA and it shows that the increasing tendency and magnitudes of set pressure are basically in accordance with the numerical modeling results. Fig. 15 represents earth pressure of case SCTB and it shows that earth pressure decreased gradually until the shield passes through the centerline of the above tunnel. The theoretical value of earth pressure is very close to the measurement but the point with minimum pressure lags 6–8 rings behind.

3.3.2. Shield driving speed control

While compared with normal crossing cases where the clearance between shield and crossing objects is bigger than 1D, in close crossings, the shield shell friction and deviation correction forces become the illegible and sensitive factor affecting the movement of adjacent objects in ground. A multi-step slow shear test on disturbed soil shows that the soil strength increased slowly and excess pore water pressure decreased with shear speed (Liao et al., 2006). It implies that the slow driving of shield benefits structure recovering of soil skeleton from disturbance and the reduction of consolidation time, or vise versa. Engineering practices prove that the heave and settlement produced by shield shell friction and correction forces can be reduced apparently by setting driving speed at 10 mm/min or even lower.

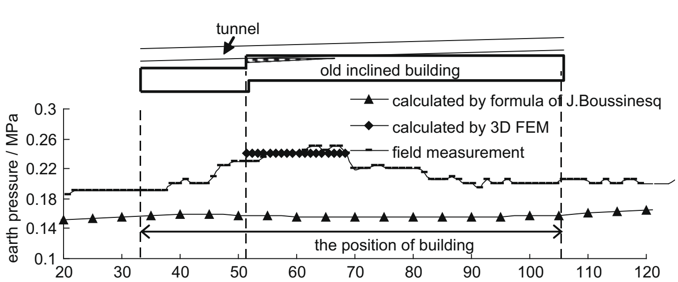

Fig. 14. Field measured and theoretically calculated values of earth pressure (case SCBA).

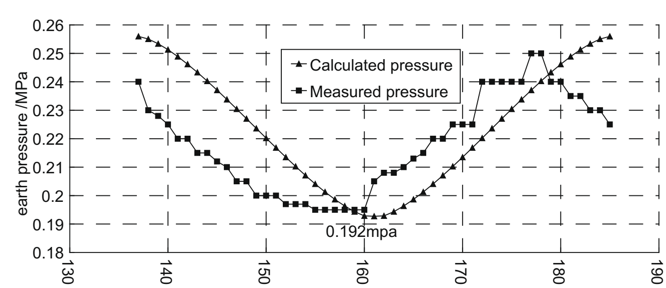

Fig. 15. Comparison between calculated and measured values of earth pressure (case SCTB).

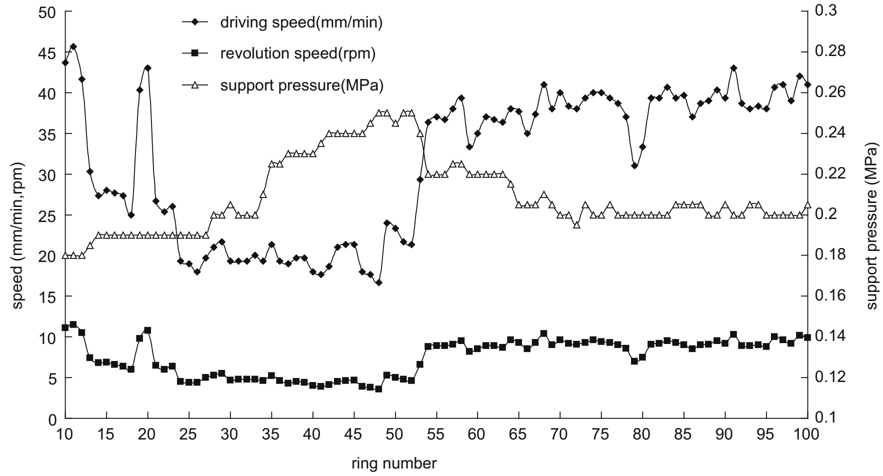

Fig. 16. The variation curves with time for parameters *n, P, v* (Liao, 2004).

3.3.3. Jacking force and shield shell friction control

The jack oil pressure will decrease gradually during the assembling of segments, which leads to backward movement of shield machine and reduction of earth pressure in shield cabinet. The reduction of oil pressure is about 0.1 MPa during stoppage according to the measurements. So it is necessary to check the oil leakage carefully and maintain the jack pressure by setting a little higher pressure just before assembling and reduce time cost of assembling.

In close crossing projects, the friction between shield shell and ground in soft clay severely influences the surrounding displacement of adjacent tunnel, which may arrive at a value of no less than the one produced by workface or shield tail gap by comparison. Grouting holes on shield shell may be used to grout bentonite into the surrounding ground to reduce friction.

3.3.4. Earth discharge volume control

The earth discharge volume is controlled by adjusting revolution speed of conveying screw (n) which is a sensitive key factor affecting ground movement but difficult to operate. When the shield driving speed is very slow, the adjustment can not achieved automatically or quickly enough to match the revolution speed (n) with pressure (p) and jacking speed (v). Under this circumstance, the manual operation is needed to be shifted at once to control their relationship. So, the statistic calculation should be done in the experimental stage to obtain their correlation curves for the forthcoming construction control process (Figs. 16 and 17). From Figs. 16 and 17, the deliberate adjustment of n can control the support pressure accurately when the driving speed (v) remains unchanged.

3.3.5. Axial deviation control of shield in curvature

During the shield driving in curvature, the changes in driving postures will result in additional ground loss volume (GVL). According to the principles of geometry, the more sides the polygon, the more close to a circle. The area of regular polygon reaches maximum. It can be deduced that one ring of shield driving can be divided equally into several driving steps (n), while in each step of driving, the deviation correction can thus be set to small values, and consequently the total GVL can be reduced by amount of n times (see Fig. 18).

3.3.6. Synchronous grouting

It is important to keep grouting volume rate in accordance with shield driving speed. Full efforts should be made to fill completely the shield tail void and balance ground pressure by controlling grouting pressure and volume according to the metrical instrument in real time. The outlet pressure of grouting pipe should be no less than the earth pressure at rest of tunnel invert and no bigger than that at crown of shield. This doing prevents workface form unfavorable stress release and squeezing of surrounding ground resulting in significant disturbance, consolidation settlement and even the expulsion of grouting from ground surface. The grouting volume per ring is changing due to geological conditions and GVL control results. In case SCBA, the grouting volume is about 195% of

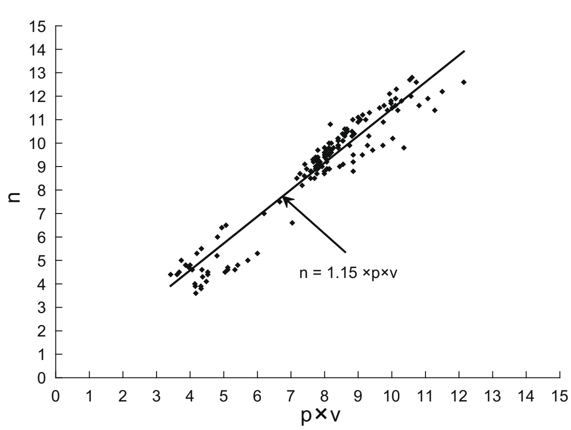

Fig. 17. Statistic relationship between n and $p \times v$ (Liao and Yang, 2004).

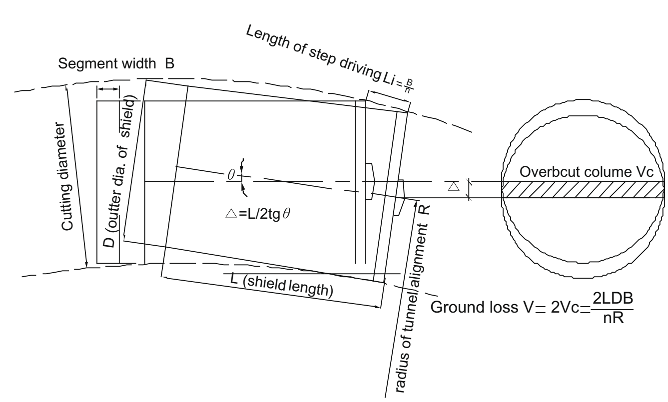

Fig. 18. GVL due to shield driving in curvature (Liao and Yang, 2004).

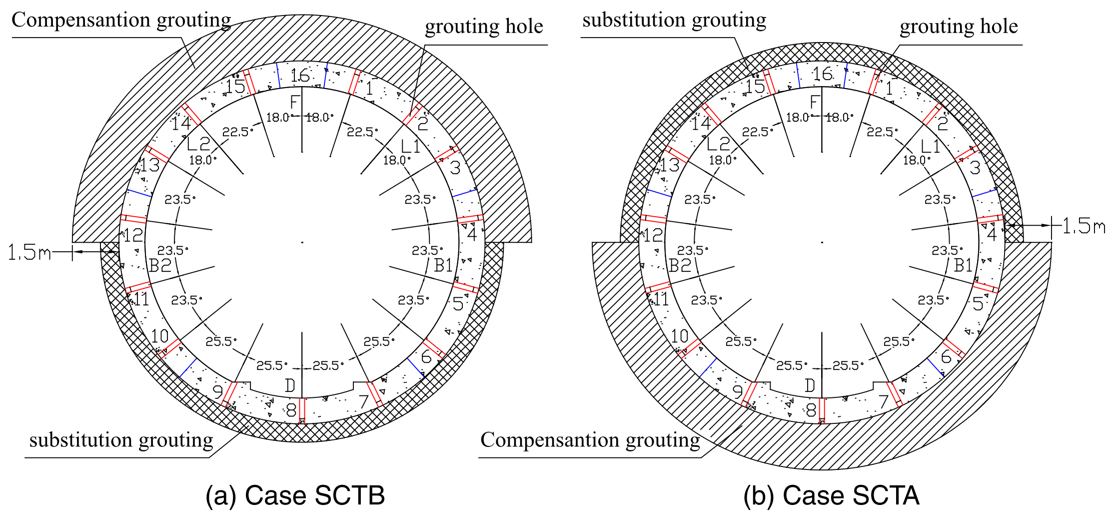

Fig. 19. Compensation grouting reinforcement.

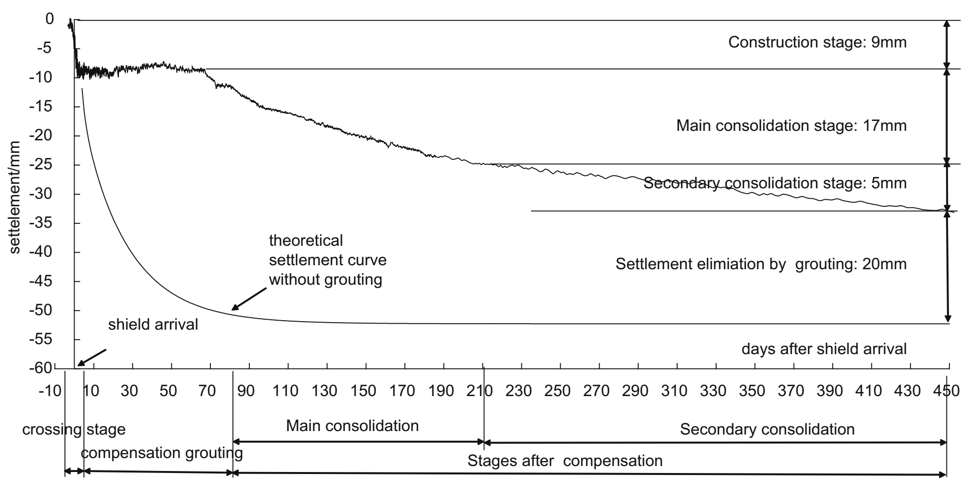

Fig. 20. The building settlement vs. time curve (from data of point with maximum settlement).

theoretical tunnel void volume, while in case SCTB, the grouting volume is about 105–130%.

3.3.7. Compensation grouting from in tunnel

In very soft clayey ground, consolidation settlement after construction is about a factor of 2-2.5 the settlement in construction, and it can develop at least half a year or more to become stable. So the additional ground reinforcement is needed to reduce and mitigate the long term settlement after construction, especially counteracting the impaction by long term train vibration.

For cases of SCTA/SCTB and SCBA, the compensation grouting reinforcement with two-shot solution grouts is needed and implemented from the pre-embedded grouting holes on the tunnel lining in order to keep the ground stable for long at the allowable settlement. The grouting principles for the reinforcement are concluded as grouting uniformly at small volume and more points for more times. The grouting parameters such as the number of grouting holes and their positions, grouting length and pulling speed as well as the grouting pressure and the grouts flow rate, are pre-selected based on the above principles before the final execution. These parameters are still needed to be optimized in the process of grouting according to the feed back data of displacement. In saturated soft clay with sensitivity at the order of 6 or more, the threshold value of displacement increment for feed back adjustment is 2 mm, a very small value for achieving minimum disturbance to ground. The grouting frequency of each hole depends on the stability of displacement development. In general, the grouting frequency decreases gradually from once per day in the beginning to once per month until the displacement rate satisfies the requirements.

As for case SCTB, the static penetration strength of the reinforced ground at the base of tunnel should reach 1.2 MPa. The whole grouting process will take long for half a year or more to 9 months depending on the specific geological conditions. The stop condition for compensation grouting in Shanghai soft ground is determined as 0.1 mm/month in terms of tunnel settlement rate and zero excess pore water pressure in disturbed ground (see Fig. 19).

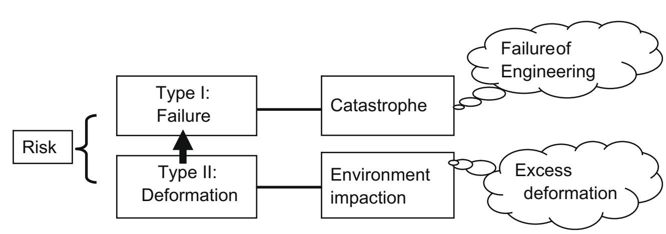

Fig. 21. Two types of risk (Liao et al., 2008b).

Table 6
Control grades classification.

Grades	Allowable GVLR (%)	Allowable GSS (mm)	Descriptions	Investigation items
Grade I	0.05–0.1	<5	Subways, high speed railways, maglev transportation lines	Location, alignment, buried depth of the targets, foundation types and structural characteristics of buildings, pipes with different diameter/material/joints/and segment length, etc.
Grade II	0.1–0.25	<10	Head conduits, main pipes of drainage system, high voltage electric pipes, densely populated residential buildings, protected architectures and other sensitive buildings, etc.	
Grade III	0.25–0.5	<20	Main roads and other important buildings, facilities and pipes, etc.	
Grade IV	0.5–0.75	<30	General environment conditions including clearing areas	

Table 7
Monitoring requirements for each grade.

Grades	Spacing	Frequency	Range	Method and accuracy
Grade I	Less than 2 m where exist running subways and maglev lines	Real time monitoring	From the point 1.5 H ahead of shield cutter face to the point 120 m behind the shield tail (H-center depth of shield)	Automatic leveling and data acquisition and the accuracy of no less than 0.1 mm
Grade II	No bigger than 5 m,	At least twice per day		1st grade manual leveling with accuracy of no less than 0.2 mm
Grade III	No bigger than 10 m,	At least once per day	From the point 1.5 H ahead of shield cutter face to the point 80 m behind the shield tail (H-center depth of shield)	2nd grade manual leveling with accuracy of no less than 0.5 mm
Grade IV	No bigger than 10 m,	At least once per day	From the point 1.5 H ahead of shield cutter face to the point 80 m behind the shield tail (H-center depth of shield)	2nd grade manual leveling with accuracy of no less than 0.5 mm

Table 8
The allowable GVLRs for monitoring (‰).

Allowable settlement(mm)	Distance from monitoring points to shield center							
	4 m	5.3 m	6 m	8 m	10 m	16 m	18 m	25 m
5.00	0.6	0.8	1.0	1.3	1.6	2.5	2.9	4.0
10.0	1.3	1.7	1.9	2.5	3.2	5.0	5.7	7.9
20.0	2.5	3.4	3.8	5.0	6.3	9.9	11.4	15.8
30.0	3.8	5.0	5.7	7.5	9.5	14.9	17.1	23.8

As for case SCBA, the compensation grouting stops when the settlement rate of the building decreases to 0.2 mm/day and the settlement rate decreases to converge at the stable value of 0.04 mm/day after 5 months (Fig. 18).Otherwise, the grouting process will need to continue for longer time. Comparison made between grouting and non-grouting cases show that the elimination of settlement by compensation grouting totally is about 20 mm and the rate of settlement at the first two weeks is reduced from 2 mm/day to 0.7 mm/day, but the total consolidation time is extended by half a year or more (see Fig. 20).

4. Control criterion

Control criterion depends on risk degrees. In terms of the severity of consequences, risk caused by close tunneling can be classified as two types: catastrophic failure (Type I) and deformation type (Type II). The catastrophic failure produces most serious consequences and is usually caused by the failure of engineering itself due to serious defects in geology, design or construction, etc. Since the deformation is out of control under this situation, this type risk may not be assessed in terms of deformation. The Type II risk is defined as a state of deformation caused by unsuitable measures adopted for deformation control which is usually can be avoided or put under control by careful and deliberate control process. The type I risk is most common in practice but, however, can be developed to the Type I risk if countermeasures are not applied in time (see Fig. 21).

To prevent the risk before it develops to final failure (Type I), the philosophy is to counteracting the Type II risk and make further classification for deformation control in order to achieve detail measures for process control. Based on a large amount of close crossing practices in Shanghai, the control criterion for displacement and correspondent monitoring requirements for different objects is enacted in Tables 6, 7 and 8 for Shanghai metro tunneling.

5. Conclusions and suggestions

(1) Three typical cases of shield crossings SCBA, SCTA and SCTB are studied, respectively, based on the successful engineering projects in Shanghai soft ground and a very small value of GVLR = 0.5% has been achieved.
(2) The impaction on environment by settlement should be assessed and experimental tunneling should be conducted before the shield passes through the running metro tunnels and important buildings in order that the control objective of GVLR can be determined. And only by this doing, the risk oriented construction plan and monitoring can be implemented to ensure both safety of shield itself and environment.
(3) Stringent criterion for GVLR is substantial for eliminating and mitigating potential risks under complicated conditions.
(4) The support pressure at workface and grouting control are most important key parameters for shield control, which

are urgently needed to be renovated in respects of craft, equipment and instrument.

(5) Based on domestic monitoring and control technology at present, pave the way for automitization of monitoring and application of artificial intelligence.

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