Numerical modeling of shield tunnelling based on the stress release ratio method

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Abstract: It is very important to evaluate ground settlement induced by underground excavation and its influence on surrounding structures. Underground excavation is done in 3-D space•and overcut phenomena usually exist. These problems can be solved using the stress release method. Rational stress release ratio (SRR) is important in computing ground settlement and the internal force of the lining, and in analyzing the change of the plastic zone surrounding the tunnel. The spatial excavation effect is modeled by controlling the SRR on the side of the surrounding rock/soil. The standard of searching SRR, the relative difference between settlement before and after lining installation is about 10%, is presented based on modeling underground excavation cases in the area of Beijing by FLAC and typical ground settlement curves induced by tunneling. By use of this standard, the different cases are modeled showing the dominating factors influencing ground settlement. According to computation, the change in ground settlement and lining internal forces under the different tunneling conditions agree with the theory of tunneling. The results indicate that the factors important in ground settlement are tunnel depth, cross-section size, and soil friction. Finally, the example of a tunnel excavation is calculated by FLAC based on this standard, and the results are similar to the monitored ground settlement. On the basis of the above work, the conclusion is drawn that the 3-D model can be simplified to 2-D when predicting tunnel induced settlements. At the same time, it is noticed that in cases of shallow and large excavation, the single SRR still has limitation, and the double or multiple SRR could be a better way to model tunneling.

Résumé: Il est très important d'évaluer le règlement au sol induit par l'excavation souterraine et son influence sur les structures environnantes. L'excavation souterraine est faite dans l'espace 3-D, et les phénomènes d'overcut existent habituellement. Ces problèmes peuvent être réglés par la méthode de dégagement d'effort. Le rapport raisonnable de dégagement d'effort (SRR) est important pour le règlement au sol de calcul et la force interne de la doublure, analysant le changement de la zone en plastique entourant le tunnel. L'effet spatial d'excavation est modelé en commandant le SRR du côté d'entourer rock/soil. Le niveau de rechercher SRR, à savoir, que la différence relative entre le règlement rayant avant et après l'installation est environ 10%, est proposé, basé sur modeler des cas souterrains d'excavation dans le secteur de Pékin par FLAC et courbes moulues typiques de règlement induits par le perçage d'un tunnel. Au moyen de cette norme, les différents cas fonctionnants de combinaison sont modelés des facteurs de domination influençant le règlement au sol. Selon le calcul, le changement du règlement au sol, rayant la force interne dans les différentes conditions de perçage d'un tunnel, sont conformes assez bien à la théorie de perçage d'un tunnel. Les résultats de calcul indiquent que l'importance d'importance pour rectifier le règlement est alternativement profondeur de tunnel, taille en coupe, et frottement de sol. En conclusion, l'exemple d'une excavation de tunnel est calculé par FLAC basé sur cette norme, et les résultats sont près du règlement au sol surveillé. Sur la base du travail ci-dessus, on tire la conclusion que le modèle 3-D peut être simplifié au 2-D quand le tunnel de prévision induit des règlements. En même temps, on le note qu'en cas d'excavation peu profonde et grande, le SRR simple a toujours la limitation, et le double ou multiple SRR pourrait être une meilleure manière de modeler le perçage d'un tunnel.

Keywords: stress release; excavation; settlement; FLAC

INTRODUCTION

Ground settlement induced by excavation in the underground environment and the assessment of its influence on adjacent buildings are important issues in urban development. Tunnel construction changes the original soil stress field, and the surrounding soil is disturbed, so surface settlement occurs. In the process of tunnelling, spatial effects appear, meaning the soil in front of the excavation face supports the soil behind, and as the tunnel excavation moves on, the effect decreases and the load on the lining increases. On the other hand, overcut phenomena usually exist. Before lining work begins the external loads are taken by shield machines, and after lining installation the loads will change. It is useful to settle these problems rationally and simply compute the internal forces in the lining and predict the ground settlement and its influence on adjacent buildings.

Stress release must be considered during the process of modeling ground settlement and lining internal force induced by shield tunneling. The research showed that stress release refers to ground conditions, excavation methods and lagging of lining installation behind excavations (Zhou et al. 1997). Obviously, 3-D modeling is the best, however the construction of the 3-D model is too complex and the calculation is time-consuming, and so it is useful to simplify the problem with the 2-D model. In the generalized dummy support force method (Sun et al, 1994), the constraint effect in horizontal and vertical directions can be simulated and the change of radial dummy support force is used to model the radial displacement release ratio of the tunnel. The original strain method (Song 1999), in which the original strain is similar to contraction strain caused by temperature drop, can be used to simulate the overcut problems in the shield method, but the disadvantage is that it is difficult to find out the true original strain. Applying the double parameter method (Azevedo et al. 2002), the stress release problem can be simulated before and during shield arrival, and the requisite parameters can be determined by ground settlement before shield arrival, but determination of the safety factor is difficult. The lining stiffness change method (Karakus & Fowell 2003) can simulate lining stiffness increase from excavation to lining installation, so stress release is avoided, however it is the same with the NATA method. In addition, the soil stiffness change method (FLAC manual 2001) simulates the spatial effect during the excavation process with stiffness reduction(less than 10% of the original stiffness). Though the method is convenient, it has shortcomings, imprecise mechanical conception and the inaccuracy of the internal forces in lining.

In this paper, based on the stress release method (SRM), 3-D tunneling is analyzed by simplification with the 2D model. During analysis, only parameter SRR (stress release ratio) was changed. Before lining installation this parameter is used to compute the tunnel wall pressure, and after lining installation it will act on the lining. SSR can be obtained using an iterative approach based on typical ground settlement curves. The SRM can be used to compute ground settlement and internal forces of lining and to analyze the change of the plastic-zone in the surrounding rock/soil.

COMPUTATION MODEL

Pressure P_0 is applied on the tunnel wall, which is in the opposite direction to the tunnel wall pressure (Figure 1).

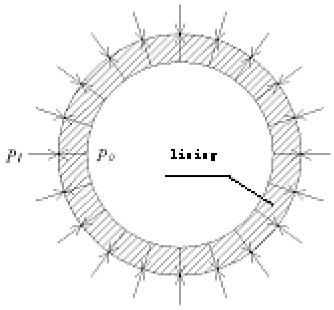


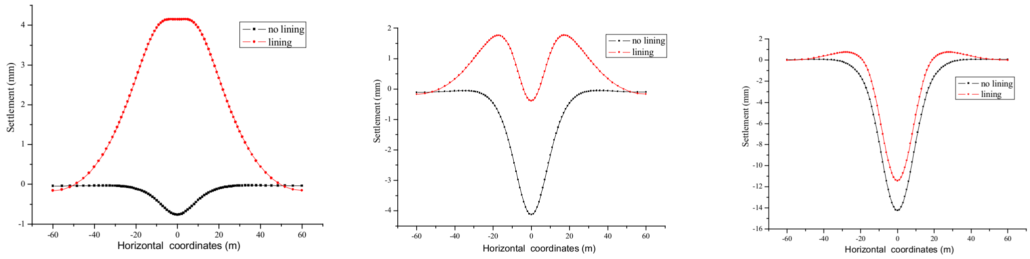
Figure 1. Calculation diagram for wall rock

Special effect can be modeled by increasing P_i step by step. SSR is defined as:

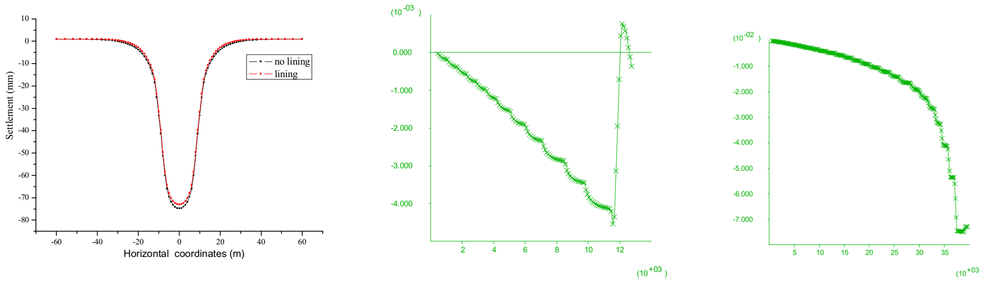
$$\lambda = P_i / P_0 \quad (1)$$

and $(P_0 - P_i)$ is the surplus load on the lining.

Figure 2 from (A) to (D) shows the comparison of ground settlement before and after lining installation: when SSR is small, the ground will rise up; whereas SSR increases, ground settlement *S* increases and is close to the ground settlement *S′* before lining installation. (E) and (F) are the maximum vertical displacement-calculation time curves with different SSR, and from the two figures it is noted that (S- S') becomes small when SSR increases.



(A) λ=0.1 (B) λ=0.3 (C) λ=0.5



(D) λ =0.7 (E) λ = 0.3 (F) λ = 0.7

Figure 2. Ground settlement at different stress release ratios

According to modern lining theory, the self-support ability of surrounding rock/soil should be fully used before lining installation, but when the tunnel is shallow in depth, large-scale settlement happens, though soil pressure on the lining is small. The curve in Figure 3 (Liu 1991) is a typical ground settlement profile. It was found that the ground settlement before lining installation was bigger than after lining installation. If a big SSR is adopted, the result agrees with the typical ground settlement curves, but the value is irrational, because excessive ground movement is not allowed. Hence, a rational SSR must be determined properly by modeling.

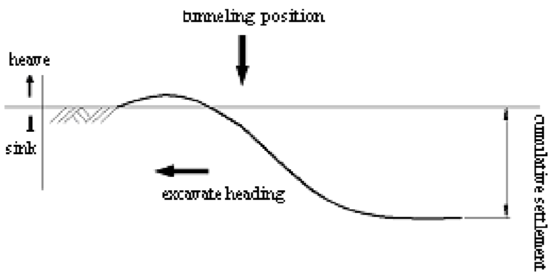


Figure 3. Typical ground settlement curve by shield excavation

In order to find a rational SSR, Δ=(S- S′)/S was determined as the control parameter, and then numerical calculations at different excavation conditions were made by FLAC. Figure 4 shows the calculation scheme.

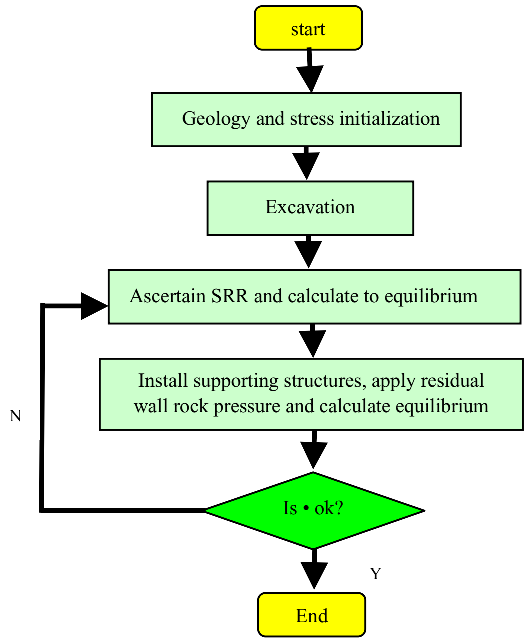


Figure 4. Scheme of FLAC calculation

The calculation results are shown in Table 1. It can be noted that SSR or pressure in the tunnel wall is related closely with strata and excavation conditions. Ground settlement varies with different Δ. In comparison, the typical ground settlement curve and engineering experiences show that Δ=0.10 is appropriate.

ANALYSIS OF GROUND SETTLEMENT AND INTERNAL FORCES IN LINING BY SRM

Analysis (Zhang 2004) revealed that the depth and size of the tunnel and soil friction angle have larger influences on surface settlement than horizontal lateral pressures, soil cohesion and shield advance. In the following analysis, the importance of the former three factors on surface settlement and internal forces in lining were analyzed to validate the applicability of the SSR method. According to the geological conditions, the numerical values of the three factors have three levels, as listed in Table 2.

Table 1. Comparison of ground settlement at different Δ and working cases

		Δ=0.2		**Δ=0.15**		**Δ=0.10**		**Δ=0.05**	
		λ	**settlement(cm)**	**λ**	**settlement (cm)**	**λ**	**settlement (cm)**	**λ**	**settlement (cm)**
A	S	0.35	3.803	0.375	4.622	0.425	7.984	0.475	714
	S′		3.137		3.979		7.379		714
B	S	0.5	1.424	0.55	1.934	0.6	2.682	0.65	4.120
	S′		1.142		1.683		2.463		3.927
C	S	0.425	1.765	0.45	2.0	0.5	2.58	0.575	3.869
	S′		1.461		1.711		2.338		3.696

case A: R: 4m H: 10m φ: 16° cohesion: 10Kpa
case B: R: 3m H: 15m φ: 21° cohesion: 10Kpa
case C: R: 5m H: 20m φ: 26° cohesion: 10Kpa

Table 2. Test level of factors

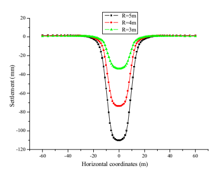
	R (m)	**H (m)**	**φ (°)**
Case1	5	20	16
Case2	4	15	21
Case3	3	10	26

Table 3. Different working cases results of ground settlement and internal force at Δ=0.1

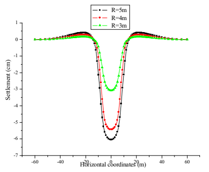
No.	R (m)	H (m)	φ (°)	λ	S′ (cm)	S (cm)	$\|N\|_{max}$ (KN)	$\|M\|_{max}$ (KN.m)
1	5	20	16	0.15	1.77	1.86	1843	305.5
2	4	20	16	0.025	0.097	0.094	1602	373.5
3	3	20	16	0.325	2.18	1.97	825.2	190.1
4	5	15	16	0.275	4.09	3.68	1279	203.2
5	4	15	16	0.35	4.38	4.0	887.2	178.8
6	3	15	16	0.40	3.0	2.74	573.3	131.1
7	5	10	16	0.375	11.83	11.0	822	129.2
8	4	10	16	0.425	7.97	2.74	569.7	116.4
9	3	10	16	0.425	3.9	3.59	400.7	94.31
10	5	20	21	0.30	1.83	1.65	1508	246.5
11	4	20	21	0.40	2.03	1.83	1020	214.4
12	3	20	21	0.525	1.85	1.68	576.9	140.1
13	5	15	21	0.45	4.57	4.20	968.2	158.8
14	4	15	21	0.50	3.50	3.20	681.9	144.5
15	3	15	21	0.575	2.26	2.04	405	96.5
16	5	10	21	0.475	6.69	6.05	688.7	114.3
17	4	10	21	0.55	5.89	5.43	446.3	94.76
18	3	10	21	0.575	2.59	2.35	272.9	65.64
19	5	20	26	0.50	2.57	2.33	1078	170.2
20	4	20	26	0.575	2.15	1.95	716.5	143.6
21	3	20	26	0.675	1.55	1.42	392	93.28
22	5	15	26	0.575	3.56	3.27	740.6	118.5
23	4	15	26	0.65	2.97	2.73	472.1	97.81
24	3	15	26	0.725	1.86	1.71	260.1	60.64
25	5	10	26	0.60	7.72	7.20	522.2	83.12
26	4	10	26	0.65	3.84	3.48	346.7	73.44
27	3	10	26	0.70	1.77	1.61	180.1	43.11

These combinations were input in to the calculation model. Afterwards, surface settlements and internal forces in the lining were obtained (Table 3). The importance of the three factors was analyzed in the following situations:

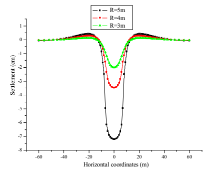
When R is constant and H and φ is variable



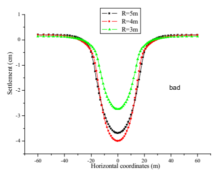
(A) H=10m φ=16°



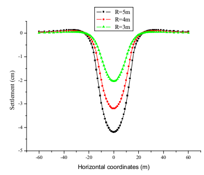
(B) H=10m φ=21°



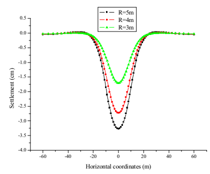
(C) H=10m φ=26°



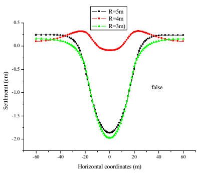
(D) H=15m φ=16°



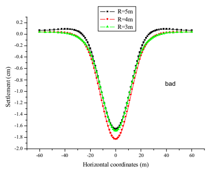
(E)H=15m φ=21°



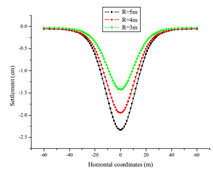
(F)H=15m φ=26°



(G)H=20m φ=16°

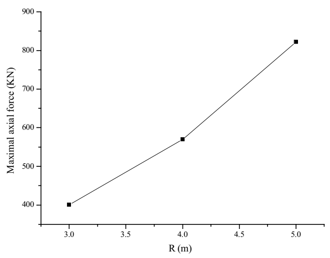


(H)H=20m φ=21°

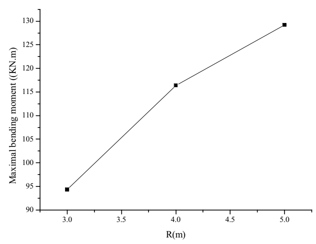


(I)H=20m φ=26°

Figure 5. Ground settlement at different R



(A) comparison of the maximal axial force



(B) comparison of the maximal bending moment

Figure 6. The maximal internal force of structure at different R

It can was shown (Figure 5) that the maximum surface settlement and the width of the settlement trough both increase with tunnel radius increase. Figure 6 shows that the maximal axial force increases linearly with tunnel radius, and the maximal moment rises rapidly at first and then slowly. These agree with the theoretical results and practice. At the same time, the SRR also increases as does *R*. The time of lining installation can be predicted with SRR. When the cross-section is large, the SRR is also large, so lining installation should be early, or it will be necessary to control the overcut and grouting.

When φ is variable but H and R constant, or when H is variable, R and φ is constant

When φ is variable and H and R are constant, the maximum ground settlement generally decreases as the friction angle of soil increases.

The width of the settlement trough is defined as the distance between two spots where the ground settlement is zero. As φ increases the trough width increases. The results show that the maximal axial force and moment decreases as φ increases, indicating that the self-support ability of the soil becomes stronger when φ increases and the pressure on the lining decreases, and its internal force decreases, too.

When H is variable and R and φ is constant, ground settlement decreases and the width of the subsidence trough increases. With the depth increase, internal forces in the lining rise more and more rapidly. According to tunnelling theory, arching effect becomes strong when H increase and the stress of the wall rock stabilizes gradually. But the figures show that the pressure in the soil doesn't reach stabilization when H is less than 20 m.

Modeling of tunnelling processes by SRR reflects the relationship between ground settlement, internal forces and excavation conditions. When φ changes, the error rate is highest, then R, and H. The importance of H, R and φ on ground settlement decrease in turn.

CASE STUDY

An experimental segment of a shield tunnel in Beijing, R=6m, depth=15m, and the computation parameters are listed in Table 4.

Table 4. Soil parameters for computation

Soil class	H	E	μ	φ	C	ρ
Filling soil	4	5	0.3	20°	8	1900
Silty clay	8.5	12.1	0.28	19°	41	2030
Middle- and coarse-grained sand	3.9	32.5	0.25	34°	0	2020
gravel	3.5	40	0.22	50°	0	2150
Arenaceous silt	2.7	30	0.28	36°	31	2000
Middle- and coarse-grained sand	below	38	0.26	40°	0	2040

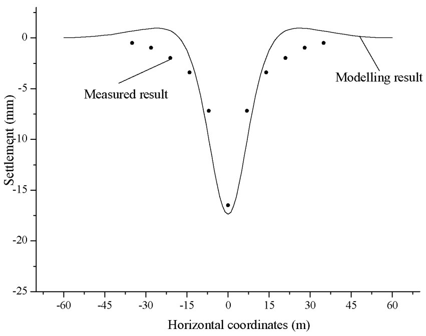


Figure 7. Comparison of modeling and monitoring results

By SRM, the results in Figure 7 indicate that the biggest surface settlement is close to the filed monitored data, but there is a slight uplift in the ground settlement curve near the settlement trough. A possible reason is the use of the unique SRR. In tunnel construction, its radius often changes. In the case of shallow and large excavations, SRR is bigger at the top than at the bottom of the tunnel so single SRR has limitations in this case.

CONCLUSIONS AND DISCUSSIONS

Based on numerical computation and typical ground settlement curves induced by tunnelling, the standard of looking for SRR was put forward. The factor analysis was done by FLAC, and during the calculation the standard was used to obtain SSR. The change laws of surface settlement and internal forces in lining agree with the theoretical prediction. Based on this standard, the example of a tunnel excavation was calculated by FLAC, and the surface settlement derived was similar to the in-situ value. This method is effective when used to simulate 3-D problems using a 2-D model.

By the SRM, the main three factors which affect surface settlement were studied using FLAC. The conclusion was that the significance of the three factors are, in turn, tunnel depth, excavation size, and soil friction angle.

In this research, Mohr-Coulomb failure criterion was adopted. The computed settlement values scatter differently using different failure models (Oettl 1998). Because tunnelling means that unloading in the soil around the tunnel occurs, it is better that a model that reflects the unload process is used in the numerical analysis.

Surface settlement by tunnel excavation occurs in 3-D space. In modern cities, the aim is to study surface settlement to evaluate the excavation influence on adjacent buildings. But the failure of buildings doesn't happen immediately and is a process of accumulation, so the final settlement value is not valuable in this instance.

In this research, a unique SRR was used. In the case of shallow and large excavations the double or multiple SRR is a better way to model tunneling. The 2-D iteration method is simple and clear, and can be used to find an appropriate SSR and calculate surface settlement.

The method is simplified, and can only be applied in certain conditions, so Δ=0.10 is only applicable for normal construction conditions. In other excavation conditions, the applicability of this method requires validation by further study.

The main limitation lies in the analysis in 2-D space, so the development process of surface settlement could not be modeled directly. In addition, the properties of a soil are different in different areas, so Δ=0.10 should be adjusted. Therefore, its applicability needs to be checked in practice.

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