INTERACTION BEHAVIORS DURING THE EXCAVATION FOR THREE-PARALLEL TUNNEL

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ABSTRACT

The freeway No.1 and No.3 located on the western corridor of Taiwan opened in 1978 and 2004 respectively. In recent years, as the constructions of expressways has been expanded toward the mountainous terrain of Taiwan, high percentage of tunneling and long tunnels on the expressway in mountainous areas are inevitable. For the sake of constructions and the managements in the operation stage, sometimes a separate pilot tunnel is arranged between the two main tunnels. As a result, a three-parallel tunnel is formed; the Hsuehshan Tunnel of Taipei-Ilan Expressway Project is as an example. In this paper, the interaction behaviors during the excavation of three-parallel tunnel are investigated by the numerical analyses. The study shows that the excavation behaviors are relevant to the geology and the engineering layout. In general, the bigger excavation area, worse geological condition, higher overburden, narrower rock pillar width and more un-equilibrium lateral stress coefficients in the tunnel, the more obvious deformation and the interaction behaviors it will be. When the above-mentioned situations happen during the excavation, it is necessary to take some measures such as dewatering, multi-step excavation faces, shorter round length and heavier supports for the stability of tunnel construction.

Keywords: interaction behavior, main tunnel, separate pilot tunnel, rock pillar, overburden, lateral stress coefficient.

INTRODUCTION

Since three quarters of Taiwan Island are mountainous and hill terrains, most of the urban areas are located in the highly developed western plane on the island. In order to balance the regional development and eliminate the difference between the urban and rural areas, the constructions of domestic traffic are extending toward the mountainous terrains. Taking the projects of expressway as example, the Taipei-Ilan Expressway Project, the Eastern Expressway Project and the Nantou Section of Expressway No.6 are under construction or in the stage of detail design. Many tunnels in these projects have the features of long length and big cross-section. Therefore, it is important to solve the problems such as complicated geology, inadequate overburden and abundant underground water flow for the tunnel design and construction.

For the requirements of transportation and construction, most road tunnels are designed as twin main tunnels. However, some long road tunnels have a separate pilot tunnel between the two main tunnels, like the Hsuehshan Tunnel is a good example of three-parallel tunnel, which excavation behaviors are more complicated than the single or twin tunnels. In apply with the raveled and heterogeneous engineering conditions of Hsuehshan Tunnel, the issues of tunnel cross-section, rock mass classifications, rock pillar widths, rock overburdens and lateral stress coefficients are investigated by the numerical analyses with the PLAXIS program, which shows the tunnel excavation behaviors and the interaction effects among the adjacent tunnels are relative to the issues mentioned above.

Generally speaking, the tunnel deformation increases and the interaction effects for adjacent tunnel become more obvious under the circumstances of bigger excavation face, worse geological conditions, higher overburden and slim rock pillar width. The lateral stress coefficients affect the tunnel deformation as well as the plastic zone surrounding the excavated hole. The analyses show that the deformation of circular cross-section tunnel

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is less than that of horseshoe shape tunnel; also the interaction behaviors for these two cross-sections are different. In the process of excavation, if the tunnels have the unfavorable problems of geology, topography and engineering layout, some countermeasures such as dewatering, grouting, multi-step excavation faces, shorter round length and advanced forepolings are necessary for the stability of tunnel construction.

NUMERICAL ANALYSES AND PARAMETERS DECISION

This paper use the finite element package PLAXIS 7.2 for the numerical analysis, the package was developed by the Technical University of Delf in the Netherlands in 1987. The initial function of this package was to analyze the river embankment on the soft ground. In subsequent years, PLAXIS was extended to cover most other areas of geotechnical engineering. This package has some special features such as mesh generation, support modeling, generation of pore pressure, staged constructions etc. (Brinkgreve et al.1998)

The Assumptions of Numerical Analysis

Using the numerical analysis to simulate the tunnel excavation, sometimes it doesn't match with the practical engineering. Therefore, some assumptions are taken into account under the reasonable range. In this article, the assumptions for numerical analysis are as follows (Sinotech 1991):

1. The analysis models

   The analyses are taken by the models of two-dimensional and plane strain.

2. The material models

   Select the Mohr-Coulomb as the model of failure criterion, and the stress-strain relationship is considered as elastic perfect-plastic model.

3. Lining materials

   For simplicity's sake, presume the primary support of tunnel is shotcrete lining, and using the beam elements to model the tunnel linings.

4. Creep behaviors

   Suppose the tunnel deformation only affected by the works of excavation and support, the effect of creep is not relevant to the analyses.

5. The excavation sequences

   Assuming the tunnels are excavated by full-face, it didn't divide by the multi-step excavations of crown, bench and invert.

Tunnel Cross-sections

Two excavation methods were adopted during the construction of Hsuehshan Tunnel, one is drill & blast method, which cross-section is horse-shoe shape, the cross section area for main tunnel and pilot tunnel are 110m^2 and18 m^2 respectively; the other one is TBM method, which cross section is circular shape, the diameters of main tunnel and pilot tunnel are 12 m and 5 m respectively. To make the calculation easier, the geometry configurations of cross section mentioned above are not quite identical to the actual project.

Material Parameters Decision

The parameters derived from the laboratory tests usually use the intact rock samples, however, the rock mass in the field site is affected by the weathering, discontinuities and underground water flow etc., as a result, the parameters derived from the test are not completely consistent with the in-situ situations. The parameters adopted in this article mainly derived from the field geological investigations and the back analyses of tunnel monitoring data (Sinotech 2004). The suggestions from the package manual and the former empirical equations are also be referenced for the decision of parameters. The rock mass of Hsuehshan Tunnel are divided by six classifications, and the parameters of class No.II, IV andVI are listed in Table 1. The value of ΣMstage in Table 1 means the rock mass stress release, which should be less than 1.0 (Brinkgreve et al.1998).

The shotcrete lining is adopted for tunnel supports in the analyses, the axial compressive stress of shotcrete is 210kgf/cm2, the Young's modulus E is around 2.1e7kN/m2, and the Poisson's ratio ν is 0.17. For simplicity, the reduction of strength for green shotcrete and the poor quality of spraying work are negligible. Contradictorily, the other supports like steel ribs, rock bolts, forepilings are not taking into account in the numerical calculations. The parameters of support material for main tunnel and pilot tunnel are listed in Table 2.

Table 1 Material properties of rock mass class Ⅱ, Ⅳ andⅥ

Parameter	Unit	Rock mass classification		
		II	IV	VI
Dry rock mass weight γdry	kN/m³	23	23	23
Wet rock mass weight γwet	kN/m³	25	25	25
Deformation modulus Em	kN/m²	3.0e6	1.2e6	5.0e5
Poisson's ratio v	-	0.25	0.25	0.30
Cohesion c	kN/m²	1000	300	100
Friction angle ϕ	°	35	30	25
Dilatancy angle Ψ	°	5	0	0
Rock mass stress releaseΣMstage	%	85	75	65

Table 2 Material properties of the tunnel lining

Tunnel	Parameter	Unit	Rock mass classification		
			II	IV	VI
Main tunnel	Shotcrete thick. t	m	0.15	0.20	0.25
	Young's modulus E	kN/m²	2.1e7	2.1e7	2.1e7
	Normal stiffness EA	kN/m	3.15e6	4.2e6	5.25e6
	Flexural rigidity EI	kN m²/m	5906	14000	27344
	Weight w	kN m/m	3.6	4.8	6.0
	Poisson's ratio v	-	0.17	0.17	0.17
Pilot tunnel	Shotcrete thick. t	m	0.10	0.15	0.20
	Young's modulus E	kN/m²	2.1e7	2.1e7	2.1e7
	Normal stiffness EA	kN/m	2.1e6	3.15e6	4.2e6
	Flexural rigidity EI	kN m²/m	1750	5906	14000
	Weight w	kN m/m	2.4	3.6	4.8
	Poisson's ratio v	-	0.17	0.17	0.17

NUMERICAL ANALYSIS RESULTS AND INVESTIGATIONS

In this chapter, the issues of tunnel cross-section, rock mass classification, rock pillar width, rock overburden and lateral stress coefficients are investigated. The results of analyses are described below (Lee 2004):

Different Tunnel Cross-sections

In this section, the tunnel excavations affected by the cross-section shape and area are investigated. In favor of comparison, the analyses assumed the rock mass classification is No.Ⅳ, the overburden is 300 m above the tunnel, and the lateral stress coefficient is equal to 1.0. The investigations are described by the single hole and three parallel holes respectively.

1. Single Hole Excavation

Hsuehshan Tunnel is composed by two main tunnels and one separate pilot tunnel. During the process of construction, the drill & blast and TBM excavation methods were adopted simultaneously. The cross-section of drill & blast is horseshoe shape, while the cross-section of TBM method is circular. The displacements calculated from the analyses for each tunnels on different cross-section shapes are listed in Table 3 and Figure 1. It can be seen from the table and figure, the bigger of the cross-section, the more enormous of displacement, and the displacement of horseshoe cross-section is generally bigger than that of circular cross-section.

The displacement distributions of main tunnel on the horseshoe and circular cross-section are shown in Figure 2 and Figure 3. From the figures it can be seen

Table 3 The displacements of different cross sections

Tunnels	Extreme total displacements (mm)	
	Horseshoe shape	Circular shape
Pilot tunnel	34.44	21.95
Main tunnel	79.40	59.35

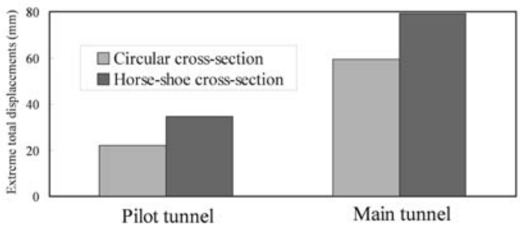

Figure 1 The comparisons of displacement on different cross-sections

that the amount of displacement of circular cross-section is less than that of horseshoe shape cross-section, and the displacement distributions of circular cross-section are more uniform than that of horseshoe shape cross-section. During the process of excavation on the horseshoe shape cross-section, there is a substantial amount of displacement at the invert, as shown in Figure 2. To avoid the instability caused by the heave of invert, the invert lining should be closed in the due time, and the field monitoring can't be negligible in the period of construction.

2. Three Parallel Holes Excavation

The Hsuehshan Tunnel is a three-parallel road tunnel which layout as shown in Figure 4. For the geological investigations and dewatering purpose, the pilot tunnel was excavated first, subsequently by the northbound main tunnel, and the southbound main tunnel was the last breakthrough. In this section, the interaction behaviors for the three-hole excavation are investigated. The assumptions of cross-section is circular shape, rock mass classification assume No.Ⅳ, the distance between the centerline of main tunnels is 60 m (i.e. the centerline distance between main tunnel and pilot tunnel is 30 m), and rock overburden is 300 m above the tunnel. The lateral stress coefficient is presumed equal to1.0, and the underground water levels are negligible. After the numerical analyses, the extreme total displacements for each construction stage as shown in Table 4 and Figure 5. It can be found from the above date that the displacement of pilot tunnel increased form 21.14 mm to 30.21 mm (approximately increased 43%) owing to the excavation of northbound main tunnel. The subsequent excavation of southbound main tunnel also caused the pilot tunnel increased its displacement up to 33.44 mm (totally increased 58%). The extreme total displacement

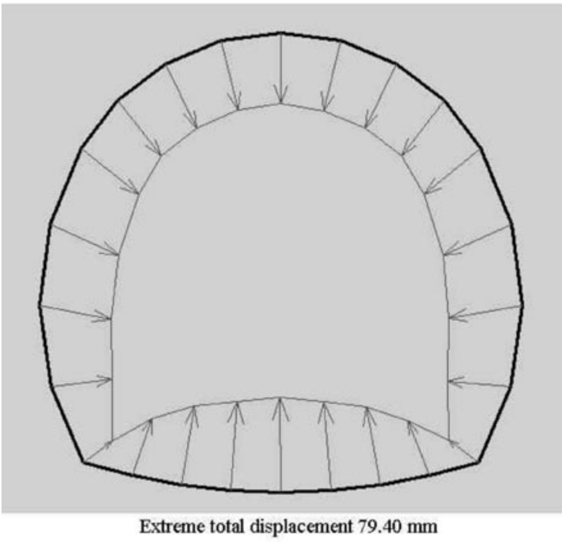

Figure 2 The displacement of main tunnel (Horseshoe shape)

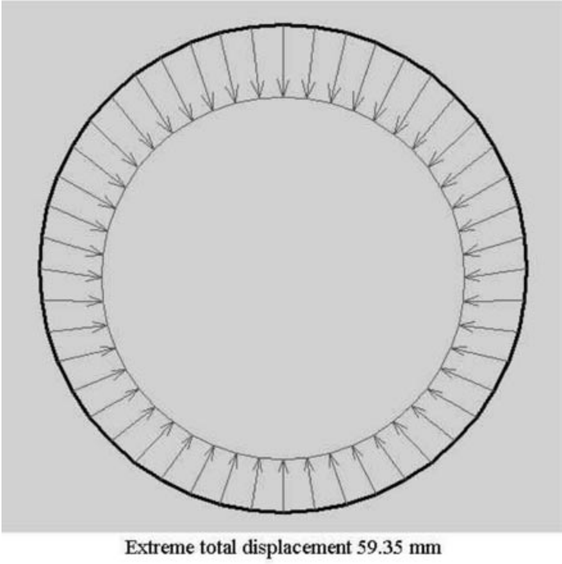

Figure 3 The displacement of main tunnel (Circular shape)

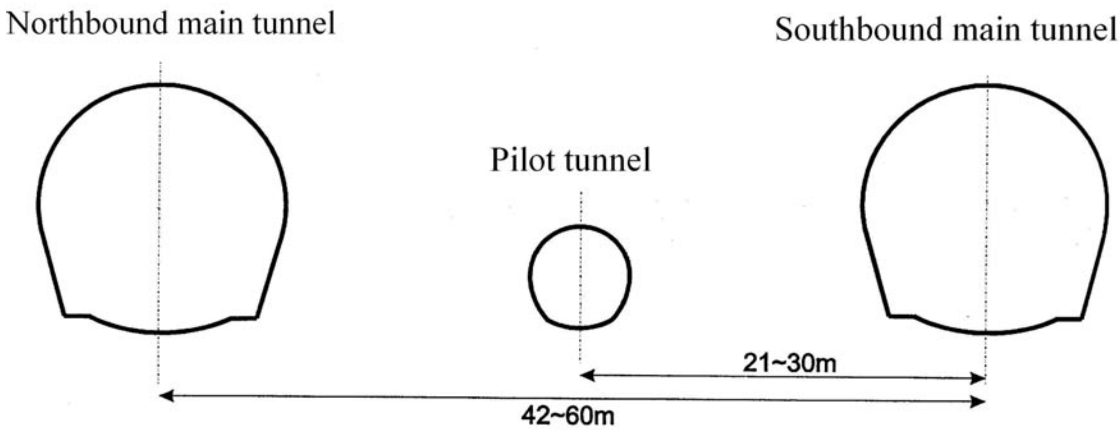

Figure 4 The cross-section layout of Hsuehshan Tunnel

of northbound main tunnel also increased from 59.63 mm to 65.05 mm (approximately increased 9%) due to the subsequent excavation of southbound main tunnel. In this study case, the displacement of pilot tunnel toward the northbound main tunnel in the second stage construction, while it kept equilibrium after the third construction stage, as shown in Figure 6 and Figure 7 respectively.

Different Rock Mass Classifications

There are six rock mass classifications for Hsuehshan Tunnel, namely, classⅠtoⅥ. In this section, the tunnel excavations affected by the rock mass classification are investigated, and the rock mass class Ⅱ, Ⅳ and Ⅵ are taken for examples to be discussed. For the reason of comparison, it assumed the overburden is 300 m, the lateral stress coefficient is 1.0, and the underground water levels are negligible in the analyses. The parameters for the rock mass and tunnel lining are listed in Table 1 and Table 2.

1. Single Hole Excavation

After the numerical analyses, the extreme total displacements for rock mass classification Ⅱ, Ⅳ and Ⅵ are shown in Table 5 and Figure 8. From the results of analyses, it can be found that the rock mass classification has a strong effect on the tunnel displacement. To avoid the instability caused by the big deformation in adverse geological conditions, the multi-step excavation faces and the heavier support measures can be taken into account. In addition, the timing of tunnel support is quite important. General speaking, the supports should be installed in time and the invert closure should be placed quickly in the horrendous ground conditions.

2. Three Parallel Holes Excavation

The interaction behaviors of three parallel tunnels on different rock mass classifications are investigated in this section. It assumed that the cross-section is circular shape, the centerline distance between the main tunnels is 60 m, and rock overburden is 300 m. The lateral stress coefficient is presumed equal to 1.0, and the underground water levels are negligible. After the calculations, the extreme total displacements for each construction stages as shown in Table 6 and Figure 9. From the results we can find, if the ground condition is worse, the displacement is more enormous. Meanwhile, the displacement of the excavated pilot tunnel will be increased after the subsequently excavations of main tunnels. The percentage of displacement increment for the pilot tunnel on the second construction stage is approximately 43%; and the total increment percentage for the third construction stage is approximately 58%. These increment percentages are almost coincident for all of rock classifications.

Different Rock Pillar Widths

The centerline distance between the two main tunnels in normal section of Hsuehshan Tunnel is 60 m, but this distance reduced to 42 m gradually at the portal section

Table 4 The displacements of circular cross- section on different construction stages

Construction stages	Extreme total displacements (mm)		
	Pilot tunnel	N. main tunnel	S. main tunnel
Pilot tunnel excavation.	21.14	-	-
Northbound main tunnel excavation	30.21	59.63	-
Southbound main tunnel excavation	33.44	65.05	65.31

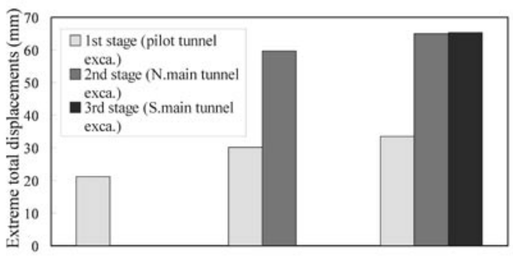

Figure 5 The comparisons of displacement of circular cross-section on different construction stages

due to the problems of alignment or land acquisition, as shown in Figure 4.The interaction behaviors of the three-parallel tunnel excavation on different rock pillar widths are investigated in this section. Similar to the previous assumptions, the circular cross-section is taken into account, the rock mass classification is presumed to No. Ⅳ, the overburden is assumed to 300 m above the tunnel, the lateral stress coefficient is presumed equal to 1.0 and the underground water levels are negligible. The following centerline distances between main tunnel and pilot tunnel are investigated in the analyses: 85 m (9B), 70 m (7B), 50 m (5B), 35 m (3B), 25 m (2B), 17 m (1B) and 12 m (0.5B). The B in the parenthesis means the sum of excavation radius of main tunnel and pilot tunnel, in here 1B = 8.5 m. The extreme total displacements for each construction stages on different rock pillar width are summarized in Table 7 and Figure 10.

From the results of analyses, the interaction behaviors of adjacent tunnels aren't obvious if the net width of rock pillar is greater than 2B. Contradictorily, the interaction behaviors get obvious if the net width of rock pillar less than 2B. Taking the net width equal to 0.5B (c/c = 12 m) as an example, the extreme total displacement of pilot tunnel deformed from 21.13 mm to 40.54 mm (increased 90%) after the excavation of northbound main tunnel. The subsequently excavation of southbound main tunnel caused the displacement of pilot tunnel up to 48.82 mm (totally increased 130%). If the rock pillar net width can be increased to 1B (c/c = 17 m), the accumulative increment percentages of pilot tunnel are 70% and 82% respectively after the subsequently excavations of two main tunnels. From the above descriptions it can be proven the importance of adequate rock pillar width. If the rock pillar width can't be kept adequate width due to the engineering or topgraphic problems, than some countermeasures such as grouting, heavier supports or glasses style tunnels can be considered for the purpose of tunnel safety.

Different Rock Overburdens

1. Three Parallel Holes Excavation

The Hsuehshan Tunnel pass through the northern end of Hsuehshan Mountain Ranges, The maximum overburden depth above the tunnel exceed 750 m. The interaction behaviors of three parallel holes on the issues of rock overburden are investigated in this section, and the overburden depths of 100 m, 300 m and 500 m are considered for the analyses. For comparison sake, it assumed that the cross-section is circular, the centerline distance between the two main tunnels is 60 m, and the rock classification is assumed No. Ⅳ . The lateral stress coefficient is presumed equal to 1.0, and the underground water levels are negligible. After the analyses, the extreme total displacements for each construction stages are shown in Table 8 and Figure 11. It can be found from the analysis results, the thicker of rock overburden, the more enormous of the displacement. The percentages of increment for the pilot tunnel displacements after the subsequently excavations of two main tunnels are 43% and 56% respectively. These percentages are almost the same for the three overburden depths mentioned in this section.

2. Portal Excavation of Shallow Overburden Depth

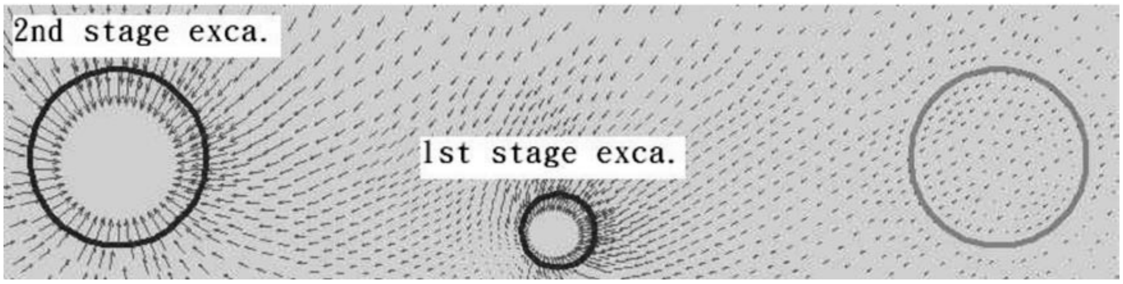

Figure 6 Displacement increments after the excavations of pilot and northbound main tunnel

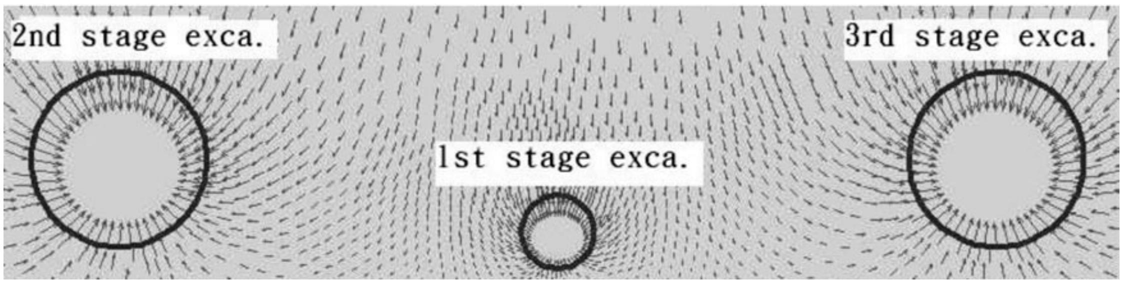

Figure 7 Displacement increments after the excavations of pilot and two main tunnels

In general, tunnel portal has the features such as adverse geological conditions, shallow overburden, slim rock pillar etc. In this section, the interaction behaviors of three parallel holes at the portal area are investigated. The tunnel cross-section is supposed horseshoe shape, the rock mass classification is assumed No. Ⅳ, lateral stress coefficient is presumed equal to 1.0, the rock overburden is supposed 12 m above the crown of tunnel, and the underground water levels are negligible. The centerline distance between the two main tunnels is 42 m (i.e. the center line distance between main tunnel and pilot tunnel is 21 m). After the analyses, the displacements on different construction stages are listed in Table 9. It can be seen from the table, the displacements aren’t so enormous in the portal area, but the displacements reach to the ground surface. From the Figure 12, it can be seen that the ground surface have subsidence of 3 mm after the excavations of tunnels. From the Figure 13 it can also be found that the heave circumstance at the invert of portal section can’t be negligible, and the deformations of main tunnels have the tendency toward the excavated pilot tunnel. To avoid the tunnel accident caused by the surface subsidence, the additional supports such as forepolings are necessary, and the invert shotcrete or concrete have to closured in the due time after the tunnel excavations.

Different Lateral Stress Coefficients

According to the plenty in-situ stress investigations hold by Hoek E. et al. the horizontal stress is obvious greater than the vertical stress within the depth of 500 m below the ground surface, and the horizontal stress approximately equal to the vertical stress below the depth of 1 km (Hoek et al. 1980) (Hoek 2000). Some back analyses taken by Kuang, et al. from the tunnel monitoring data, it can be found that the lateral stress coefficients almost equal to 1.0 in the eastern and central regions of Taiwan (Kuang et al. 1993). In the planning stage of Taipei-Ilan Expressway Project, the in-situ stress test of Hydraulic fracturing methods was taken by the Engineers, the lateral stress coefficients equal to 0.7 in some regions of the project (Taiwan Area National Expressway Engineering Bureau, 1991). In this section, the lateral stress coefficients of k = 0.5, 0.7, 1.0, 1.3, 1.5 are considered for the numerical analysis. Similar to the above assumptions, the rock mass classification is supposed No. Ⅳ?, rock overburden is 300 m above the tunnel, and the centerline distance between the main tunnels is 60 m. The underground water levels didn’t be considered in

Table 5 The displacements of different rock mass classifications

Rock mass classifications	Extreme total displacements (mm)			
	Pilot tunnel		Main tunnel	
	Horse-shoe shape	Circular shape	Horse-shoe shape	Circular shape
Class No. II	10.40	9.25	24.53	24.22
Class No. IV	34.44	21.95	79.40	59.35
Class No. VI	77.76	46.77	186.79	121.84

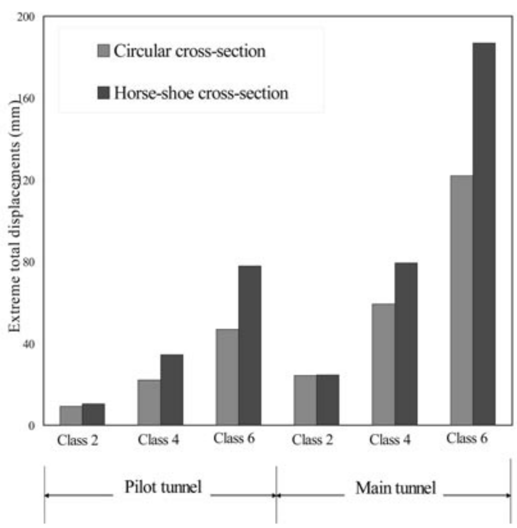

Figure 8 The comparisons of displacement on different rock mass classifications

the analyses.

1. Single Hole Excavation

In this section, the displacements of circular cross-section of pilot and main tunnels are analyzed on different lateral stress coefficients, and the extreme total displacements are summarized in Table 10. From the results, some phenomena are described below:

(1) For the circular cross-section, the tunnels have the minimum displacement when k = 1.0, whereas the displacements increased when the lateral stress coefficients greater or less than 1.0.

(2) The ratio of horizontal displacement to the vertical displacement in compliance with the increase of lateral stress coefficient, as shown in Figure 14. The horizontal displacements always exceed the vertical displacements as the lateral stress coefficient greater than 1.

(3) The plastic zones at both sides of excavation hole are extensive than that at crown and invert when the lateral stress coefficient k less than 1; contradictorily, the plastic zones at both sides of excavation hole are smaller than that at crown and invert when k exceed 1, as shown in figure 15 and Figure 16.

2. Three Parallel Holes Excavation

The interaction behaviors after the excavations of three parallel holes are investigated in this section. Similar to the assumptions mentioned above, the rock mass classification is No. IV, rock overburden is presumed 300 m above the tunnel, and the centerline distance between the two main tunnels are 60 m, underground water levels aren't considered in the analysis. After the numerical analyses, the extreme total displacements of circular cross-section on each construction stages are listed in Table 11, and the variations of displacement of pilot tunnel on each construction stages are indicated in Figure 17. It can be seen that the displacements of pilot tunnel increased after the subsequently excavations of both main tunnels as the lateral stress coefficients k less than 1. When k is greater than 1, the displacements of pilot tunnel increased after the excavation of northbound main tunnel, whereas it decreased on the subsequently excavation of southbound main tunnel. The displacement increments of horse-shoe cross-section for the second and third construction stages are shown in Figure 18 and Figure 19 respectively.

CONCLUSIONS AND SUGGESTIONS

According the numerical analyses, the displacements

Table 6 The displacements of different rock mass classifications on each construction stages

Rock mass classifications	Construction stages	Extreme total displacements (mm)		
		Pilot tunnel	N. main tunnel	S. main tunnel
Class No. II	Pilot tunnel excavation.	8.88	-	-
	North. main tunnel excavation	12.74	24.33	-
	South. main tunnel excavation	14.08	26.57	26.59
Class No. IV	Pilot tunnel excavation.	21.14	-	-
	North. main tunnel excavation	30.21	59.63	-
	South. main tunnel excavation	33.44	65.05	65.31
Class No. VI	Pilot tunnel excavation.	44.80	-	-
	North. main tunnel excavation	63.98	122.88	-
	South. main tunnel excavation	69.75	133.49	133.69

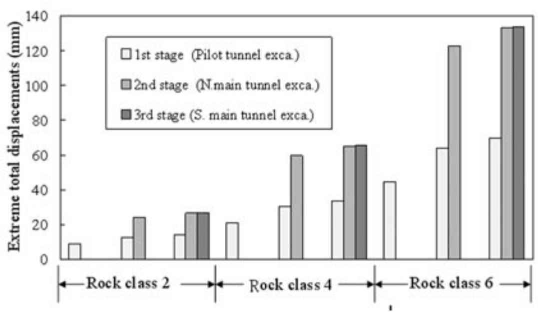

Figure 9 The comparisons of displacement for different rock classifications on each construction stages

of tunnel excavation and the interaction behaviors of adjacent tunnels are indeed affected by the issues such as geology, topography, engineering layout, etc. From the investigations of this article, some conclusions and suggestions are made below:

(1) The tunnel displacement of horseshoe shape cross-section is bigger than that of circular cross-section, and the displacement distribution on horse-shoe cross-section isn't so equilibrium as that of circular cross-section. The heave problem at the invert should be taken notice in the process of excavation.

(2) The worse of the geological condition, the more enormous of the tunnel deformation. If the tunnel excavation encounters the adverse geological conditions, the multi-step excavation faces, shorter round length and heavier tunnel supports should be taken into account; and the invert closure should be placed in the due time.

(3) Though the overburden is shallow at the portal section, but the weathering of rock mass is serious, and the rock arch is difficult to formed, sometimes the tunnel displacements after the excavations are significantly extend to the ground surface. Moreover, the interaction behaviors among the tunnels and slope make the constructions more complicated. Therefore, the designing and construction at the portal area should be taken into account prudently.

(4) The lateral stress coefficients not only affect the tunnel displacement, but also produce an effect on the plastic zone around the excavation hole. Since the Taiwan Island is located at the conjunction of tectonic plates, the effects of lateral stress coefficient to the geotechnical engineering can't be neglect (Lee et al. 2004).

(5) If the tunnel excavation encounters the abundant underground water or fractured geological conditions, the tunnels sometimes are on the instability due to the enormous deformation. During that time, the countermeasures such as the dewatering, grouting and advanced forepolings etc. can reduce the displacements significantly.

(6) The narrower of the rock pillar width, the more enormous of the displacement, and the interaction behaviors of adjacent tunnel are more evident, especially when the net width smaller than 2B (the B means the sum of radius of adjacent tunnels).

(7) The monitoring measurements in the field are very important. Reliable performance of monitoring can prevent the occurrence of accidents. Moreover, the monitoring data can also be applied to the tunneling design to achieve the goal of "design as you go".

Table 7 The displacements of different rock pillar widths on each construction stages

Centerline distance between main tunnel and pilot tunnel (Rock pillar net width)	Construction stages	Extreme total displacements (mm)		
		Pilot tunnel	N. main tunnel	S. main tunnel
C/C = 85 m (Rock pillar net width ≅ 9B)	Pilot tunnel excavation	20.85	-	-
	North. main tunnel excavation	22.91	58.03	-
	South. main tunnel excavation	24.03	58.77	58.73
C/C = 70 m (Rock pillar net width ≅ 7B)	Pilot tunnel excavation	20.71	-	-
	North. main tunnel excavation	23.57	57.37	-
	South. main tunnel excavation	25.07	58.51	59.00
C/C = 50 m (Rock pillar net width ≅ 5B)	Pilot tunnel excavation	21.05	-	-
	North. main tunnel excavation	26.16	58.06	-
	South. main tunnel excavation	28.54	60.56	61.25
C/C = 35 m (Rock pillar net width ≅ 3B)	Pilot tunnel excavation	20.87	-	-
	North. main tunnel excavation	28.52	59.52	-
	South. main tunnel excavation	31.23	63.08	64.24
C/C = 25 m (Rock pillar net width ≅ 2B)	Pilot tunnel excavation	21.04	-	-
	North. main tunnel excavation	31.66	59.66	-
	South. main tunnel excavation	33.96	65.18	67.23
C/C = 17 m (Rock pillar net width ≅ 1B)	Pilot tunnel excavation	21.19	-	-
	North. main tunnel excavation	35.79	61.48	-
	South. main tunnel excavation	38.47	71.87	73.13
C/C =12 m (Rock pillar net width ≅ 0.5B)	Pilot tunnel excavation	21.13	-	-
	North. main tunnel excavation	40.54	66.16	-
	South. main tunnel excavation	48.82	82.55	83.41

Table 8 The displacements of different overburden depths on each construction stages

Overburden depths	Construction stages	Extreme total displacements (mm)		
		Pilot tunnel	N. main tunnel	S. main tunnel
H = 100 m	Pilot tunnel excavation	6.00	-	-
	North. main tunnel excavation	8.63	16.15	-
	South. Main tunnel excavation	9.21	17.58	17.53
H = 300 m	Pilot tunnel excavation	21.14	-	-
	North. main tunnel excavation	30.21	59.63	-
	South. Main tunnel excavation	33.44	65.05	65.31
H = 500 m	Pilot tunnel excavation	36.91	-	-
	North. main tunnel excavation	52.28	106.08	-
	South. Main tunnel excavation	57.47	113.74	115.36

Table 9 The tunnel displacements at the portal section on each construction stages

Construction stages	Extreme total displacements (mm)		
	Pilot tunnel	N. main tunnel	S. main tunnel
Pilot tunnel excavation	4.44	-	-
North. main tunnel excavation	4.89	8.30	-
South. main tunnel excavation	4.84	8.30	8.25

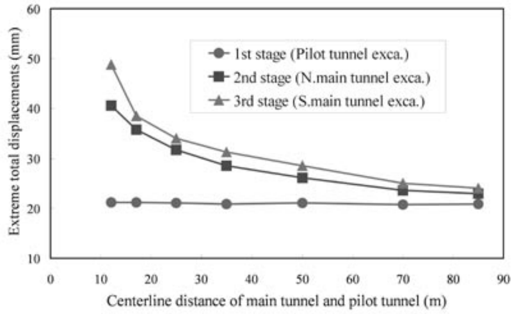

Figure 10 The variations of displacement of pilot tunnel on different rock pillar widths

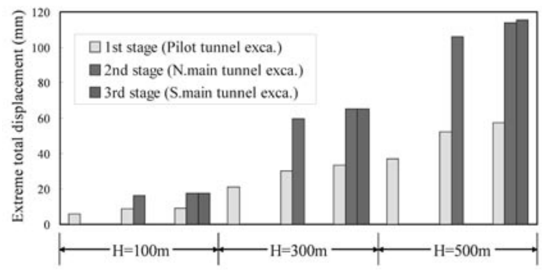

Figure 11 The comparisons of displacement for different rock overburdens on each construction stages

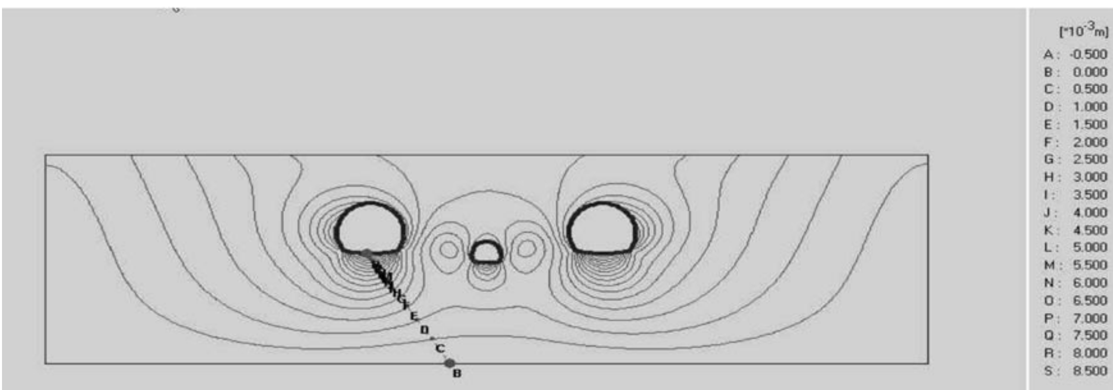

Figure 12 Displacement counters at the portal section after the tunnel excavations

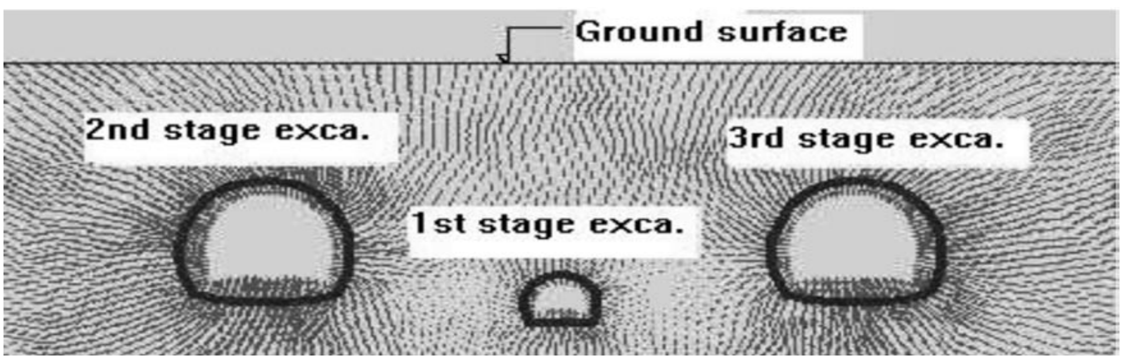

Figure 13 Displacement increments at the portal section after the tunnel excavations

Table 10 The displacements on different lateral stress coefficients (circular cross-section)

Tunnel name	Extreme total displacements (mm)				
	k = 0.5	k = 0.7	k = 1.0	k = 1.3	k = 1.5
Pilot tunnel	29.26	24.06	21.95	27.81	34.24
Main tunnel	73.86	64.10	59.35	70.52	85.50

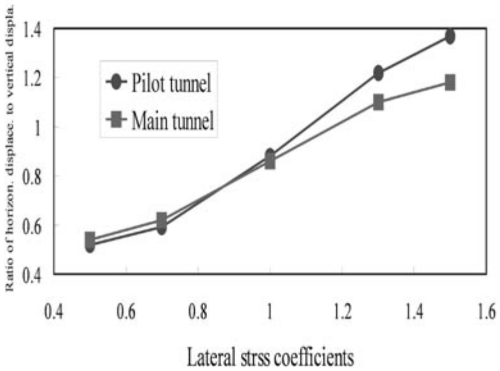

Figure 14 The ratios for horizontal displacement to vertical displacement on different lateral stress coefficients (circular cross-section)

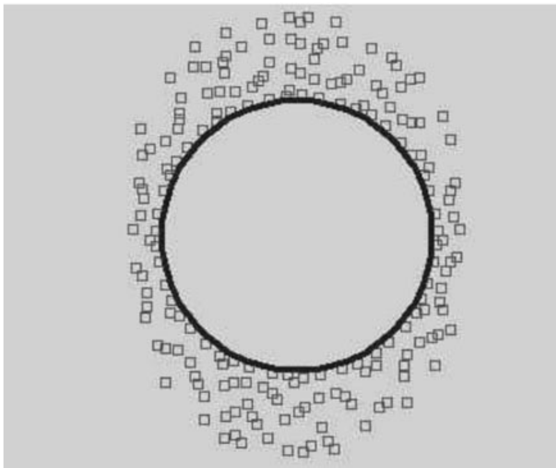

Figure 16 Plastic zone of main tunnel as k = 1.5

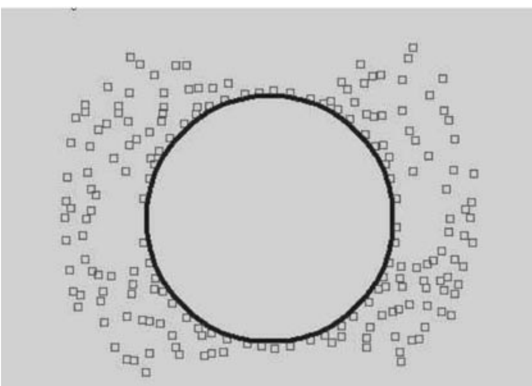

Figure 15 Plastic zone of main tunnel as k = 0.5

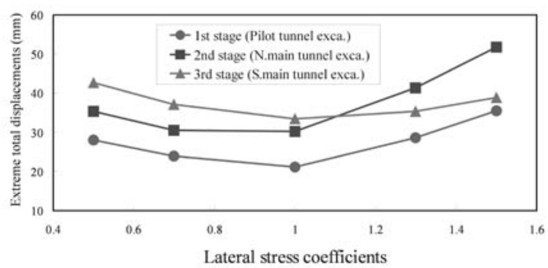

Figure 17 The variations of the displacement of pilot tunnel for different lateral stress coefficients on each construction stages (circular cross-section)

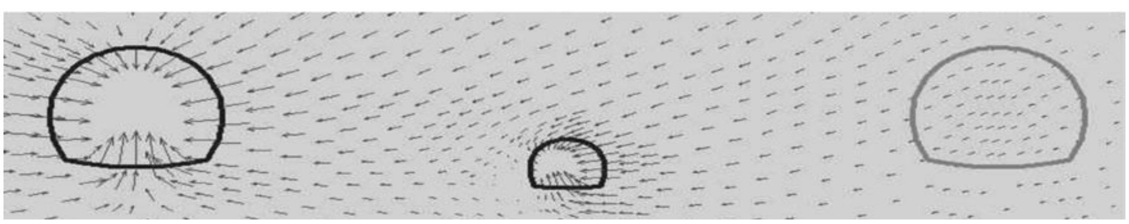

Figure 18 Displacement increments after the excavations of pilot and northbound main tunnel (k = 1.5)

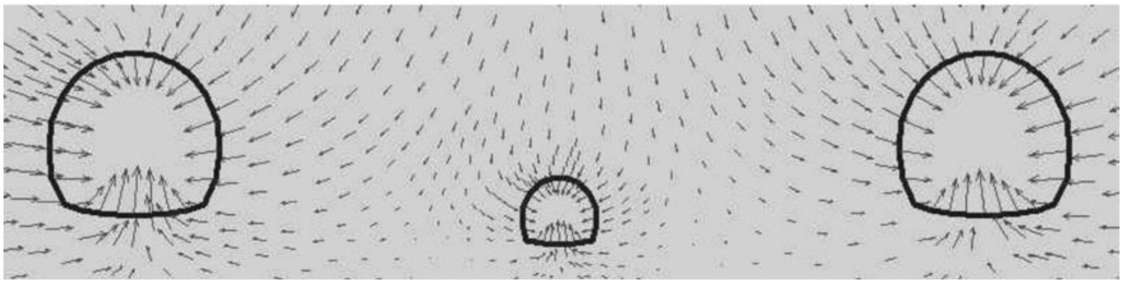

Figure 19 Displacement increments after the excavations of pilot and two main tunnels (k = 1.5)

Table 11 The tunnel displacements of different lateral stress coefficients on each construction stages (circular cross-section)

Construction stages	Extreme total displacements (mm)														
	k = 0.5			k = 0.7			k = 1.0			k = 1.3			k = 1.5		
	Pilot	N. main	S. main	Pilot	N. main	S. main	Pilot	N. main	S. main	Pilot	N. main	S. main	Pilot	N. main	S. main
Pilot tunnel	28.05	-	-	23.97	-	-	21.14	-	-	28.69	-	-	35.54	-	-
N. main tunnel	35.34	74.05	-	30.49	64.63	-	30.21	59.63	-	41.44	70.22	-	51.82	84.89	-
S. main tunnel	42.72	79.14	79.72	37.09	69.58	70.69	33.44	65.05	65.31	35.32	74.34	74.72	38.87	90.14	89.62

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