INTERACTION BEHAVIOR OF THE HSUEHSHAN TUNNELS

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ABSTRACT

Actual tunnel construction records were used to examine the tunnel interaction assessment criteria based on the results of numerical analyses. The criteria proposed was found suitable for delineating the severeness of the interaction behavior between tunnels using the information of tunnel spacing, tunnel span and rock mass strength to stress ratio at the site. Based on the criteria proposed, the tunnel arrangement adopted in the design of Hsuehshan Tunnel Project would not cause severe interaction problems between tunnels for most of the tunnel sections, with the exception of a short section of the pilot tunnel near the eastern portal area. In this area, exceptionally poor rock conditions were encountered. Instead of strengthening the lining for the whole pilot tunnel length or increasing the spacing between tunnels, strengthening the support work in a short length of the pilot tunnel near the eastern portal area was considered to be a more cost-effective solution.

Keyword: tunnel interaction, tunnel spacing, strength-stress ratio

GENERAL

Tunnel excavation will cause the re-adjustment of existing stress fields in surrounding rock masses. Therefore, the excavation of a tunnel near an existing tunnel will also cause the re-adjustment of stress fields around the first tunnel, which has been stabilized with the help of a support system. The re-adjustment of the stress field will cause further changes in the support loads and deformation of the existing tunnel. Numerous case histories of twin-tunnel and triple-tunnel construction in Taiwan in recent years have demonstrated that severe tunnel interaction can occur in tunnels without adequate spacing, especially in poor quality rock masses. In extreme cases, further increases in loose zones may cause over-stressing of support systems and even endanger a tunnel's stability.

In this paper, actual construction records were used to examine the criterion proposed by Chern and Hsiao (1997) for assessing the effects of tunnel interaction. The interactive effects of the Hsuehshan Tunnel were also reviewed using the construction records and tunnel performance observations obtained in the field.

CURRENT PRACTICES AND PREVIOUS INVESTIGATIONS

Traditionally, the interactive effect has been studied by the increase of stresses around an opening or in the pillars between openings using the stress superposition of elastic theory, such as Obert and Duvall (1967) and Ling (1948). In the mining industry, the stresses in rock pillars between openings were often estimated by assuming that the rock load was uniformly distributed over these pillars (Hoek, et al, 1980). By using this approach, Chang et al (1996) further considered the strength of rock masses. A formula for estimating the safety of rock pillars between tunnels was proposed. Based on the method proposed, however, very thick rock pillars would be required when poor quality rock masses were encountered. In some design practices, such as the "Highway Tunnel Design Guidance (1990)" issued by the Chinese government, the layout of twin tunnels was determined by considering the geologic conditions and the structure characteristics of the rock formations encountered. But in most of the design practices, the topographic condition in the portal area is the main consideration in determining the spacing between tunnels.

More comprehensive investigations were made by Chern and Hsiao (1997). In the study, numerical analyses under various combinations of tunnel spacing, rock mass quality and overburden thicknesses were conducted. Interactive effects between tunnels were

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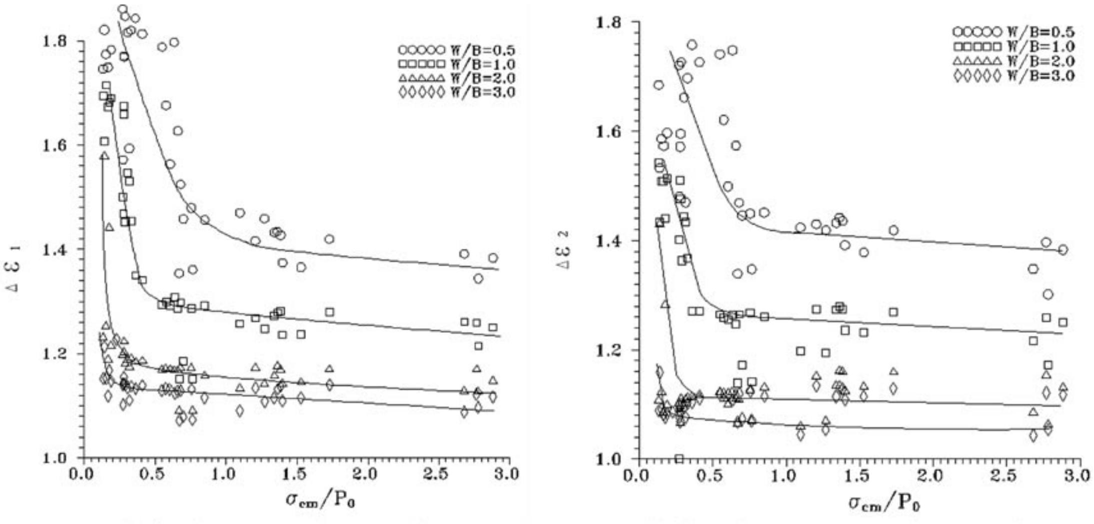

(a) for First Excavation Tunnel (b) for Subsequent Excavation Tunnel

Fig.1 The Relationship between the Increase of Tunnel Deformation, Tunnel Spacing and Strength to Stress Ratio of Rock Masses

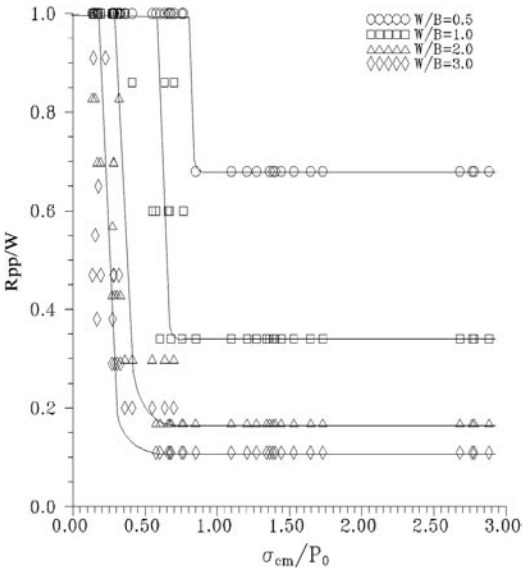

Fig.2 The Relationship between the Extent of Loose Zone in Rock Pillar, Tunnel Spacing and Strength to Stress Ratio of Rock Masses

judged by the increase in tunnel deformation and loose zone due to the subsequent adjacent tunnel excavation. It was found that the interactive effects between tunnels are closely related to tunnel spacing and the strength to stress ratio of the surrounding rock masses. The results are shown in Fig.1 and Fig.2 for the increase in tunnel deformation and extent of loose zones, respectively. Based on these results, a criterion for judging the interactive effects between tunnels, as shown in Fig.3, was proposed. In the shaded area, the interactive effects between tunnels are expected to be severe. Special consideration should be made in tunnel spacing or support systems in this case. Above the shaded area, severe tunnel interaction is not expected.

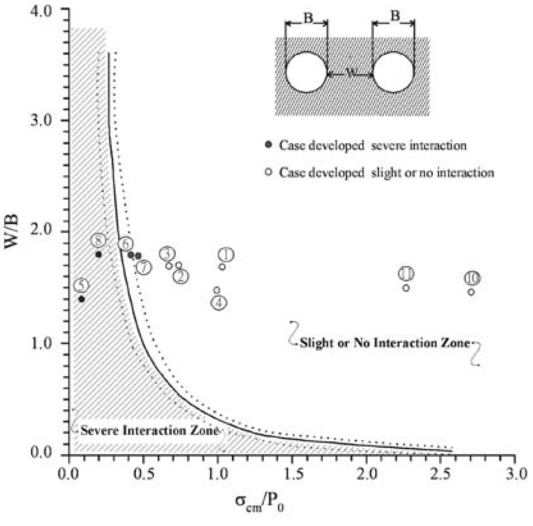

Fig.3 Proposed Criterion to Delineate the Interactive Effect

Table 1 Case Histories from Second Freeway Project

Case No.	Tunnel	Monitored Section	RMR	Rock Type	Overburden (m)	W/B	σ_{cm}/P_0	Field Performance of Pre-bored Tunnel
1	Mucha Tunnel	12k+319	44	Sandstone	80	1.7	1.16	No abnormal condition
2	Mucha Tunnel	12k+365	59	Siltstone	105	1.7	0.73	No abnormal condition
3	Mucha Tunnel	12k+460	45	Sandstone	124	1.7	0.68	No abnormal condition
4	Mucha Tunnel	11k+254	50	Siltstone	33	1.5	1.98	No abnormal condition
5	Mucha Tunnel	11k+552	32	Fault zone	120	1.4	0.10	• Severe tunnel closure • Shotcrete cracking • Steel set buckling • Tunnel remining
6	Chingmei Tunnel	13k+353	48	Sandstone with shale interbeds	75	1.8	0.41	• Shotcrete cracking • Steel set buckling
7	Chingmei Tunnel	13k+412	43	Siltstone	100	1.8	0.44	• Shotcrete cracking • Steel set buckling
8	Chingmei Tunnel	13k+453	31	Sandstone with shale interbeds	88	1.8	0.21	Shotcrete cracking
9	Futeken Tunnel	8k+884	67	Sandstone	45	1.5	4.38	No abnormal condition
10	Futeken Tunnel	8k+990	60	Siltstone	30	1.5	2.67	No abnormal condition
11	Hsintein Tunnel	16k+953	45	Sandstone	42	1.5	2.27	No abnormal condition

VERIFICATION BY CASE HISTORIES

In total there were 11 case histories with monitoring data and construction records collected from the Second Freeway Project (National Expressway No.3) in Taiwan, and they are summarized in Table 1. The plotting of roof settlement over time together with the excavation stages for two typical cases (case5 and case11) are illustrated in Fig.4 and Fig.5. Case 5 is located in poor quality rocks in a fault zone. Roof settlement due to top heading excavation stabilized at a value of around 10 cm. Significant increase in roof settlement to a level of 25 cm due to the top heading excavation of the adjacent tunnel was recorded. Severe interaction behavior may be noted in this case, although the most damaging effect to the tunnel stability is the benching down of the tunnel. In Fig.5 for case 11 where the tunnel is located in fair quality rocks, however, only a very small additional tunnel deformation was induced during the subsequent excavation of the adjacent tunnel. No significant interactive effect was observed in this case.

Plotting the data of the 11 case histories using the proposed criterion, it may be seen that all cases that developed significant interaction between tunnels fall in the shaded area where severe interaction was

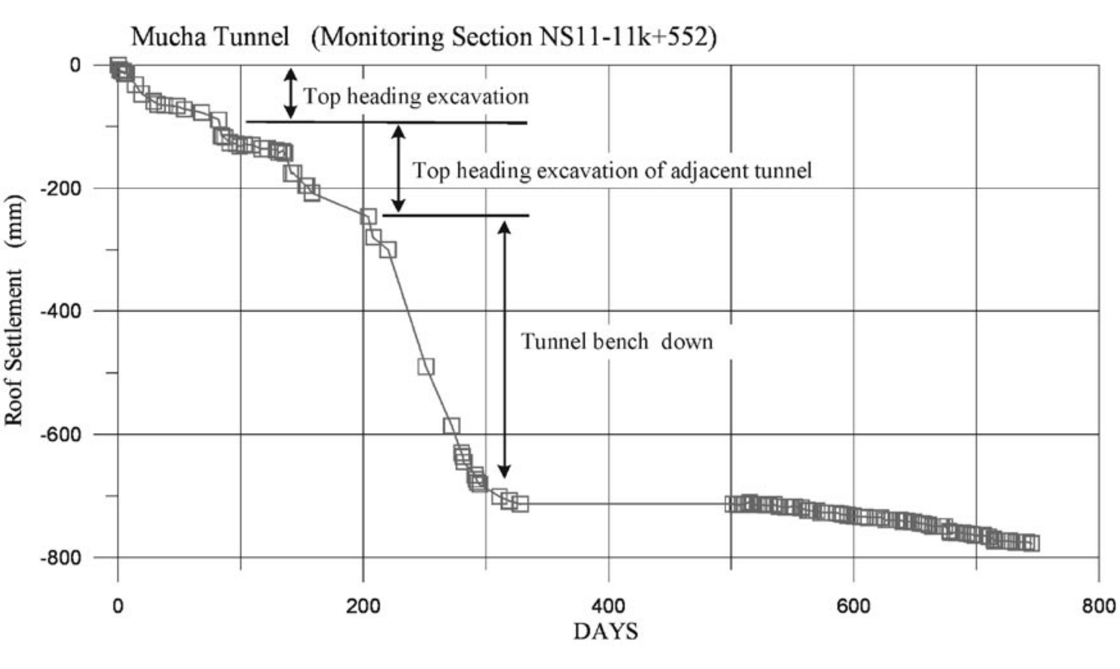

Fig. 4 Development of Roof Settlement with Excavation Progress (Case 5)

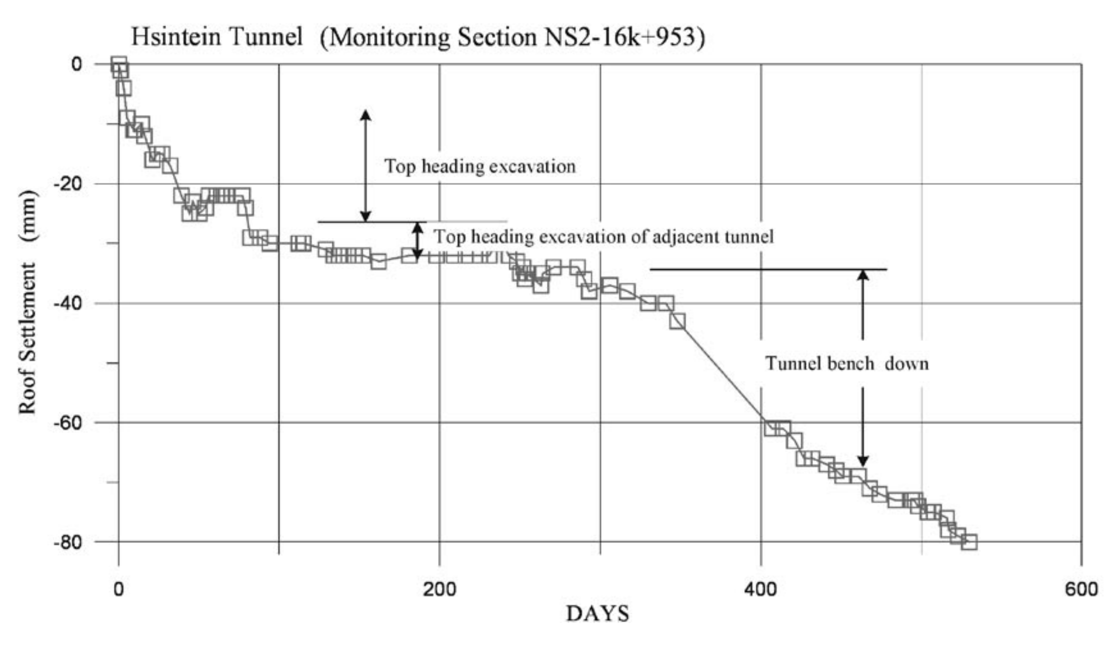

Fig. 5 Development of Roof Settlement with Excavation Progress (Case 11)

Table 2 Case Records for Hsuehshan Tunnels

Case No.	Monitored Section	Rock Formation (Rock Type)	RMR	Overbur-den (m)	W/B	σ_{cm}/P_0	Field Observation of Pre-bored Tunnel
1	Pilot tunnel 40k+580.5	Kankou Formation (argillite)	15	60	1.30	0.46	Segment lining cracking
2	Pilot tunnel 40k+328	Kankou Formation (argillite)	35	100	1.35	0.69	Segment lining cracking
3	Pilot tunnel 40k+227.5	Kankou Formation (argillite)	25	127	1.40	0.43	Segment lining cracking
4	Westbound Tube 38k+131	Szeleng Sandstone Formation (quartzose sandstone intercalated with argillite)	53	370	1.90	0.79	No abnormal condition
5	Westbound Tube 37k+875	Szeleng Sandstone Formation (quartzose sandstone)	79	370	1.90	4.97	No abnormal condition
6	Westbound Tube 37k+098	Szeleng Sandstone Formation (quartzose sandstone intercalated with argillite)	35	480	1.90	0.44	No abnormal condition
7	Westbound Tube 36k+996	Szeleng Sandstone Formation (quartzose sandstone intercalated with argillite)	45	440	1.90	0.59	No abnormal condition
8	Westbound Tube 34k+500	Tzuku Formation (sandstone)	74	580	1.90	1.26	No abnormal condition
9	Westbound Tube 34k+400	Tzuku Formation (sandstone)	74	540	1.90	1.33	No abnormal condition
10	Westbound Tube 31k+200	Makang Formation (sandstone)	69	650	1.90	0.99	No abnormal condition
11	Westbound Tube 30k+300	Makang Formation (sandstone)	77	630	1.90	1.31	No abnormal condition
12	Westbound Tube 29k+710	Fangchyao Formation (sandstone with siltstone interbeds)	45	590	1.90	0.37	No abnormal condition
13	Westbound Tube 29k+281	Makang Formation (sandstone intercalated with shale)	73	365	1.90	1.06	No abnormal condition
14	Westbound Tube 28k+660	Tatungshan Formation (sandstone with siltstone interbeds)	50	180	1.90	0.84	No abnormal condition
15	Westbound Tube 28k+255	Tatungshan Formation (argillite)	54	210	1.90	0.85	No abnormal condition
16	Westbound Tube 28k+069	Tatungshan Formation (siltstone/argillite)	56	250	1.52	0.75	No abnormal condition

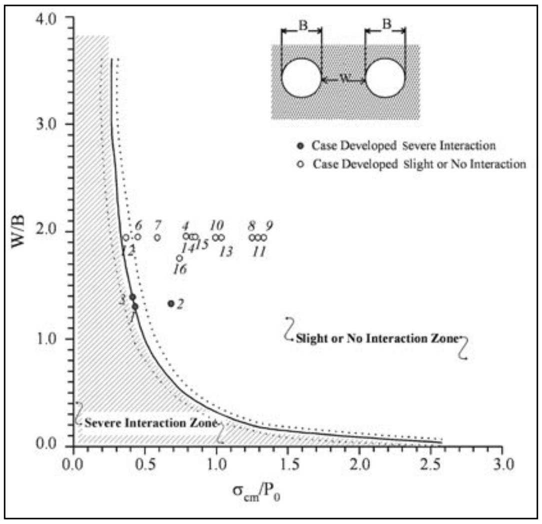

Fig. 6 Assessment of Tunnel Interaction in Hsuehshan Tunnels

expected. On the other hand, the cases with no obvious interaction fall in the area of slight or no interaction. Through the actual case records, it may be seen that the proposed criterion can delineate the interactive effect of adjacent tunnels appropriately.

INTERACTION BEHAVIOR OF THE HSUEHSHAN TUNNELS

The Hsuehshan Tunnel Project was designed as a triple-tunnel with two main tubes spaced around 48 m apart and a pre-bored pilot tunnel located at a slightly lower level in between. With numerous cross connection tunnels, including 28 passenger adits and 8 vehicle adits for emergency access and 6 ventilation chambers, the spacing between the tunnels is also an important consideration aside from the interactive effects.

Sixteen tunnel sections with more comprehensive information on rock conditions, construction records and tunnel performance observations, distributed along the entire tunnel length were selected for evaluating the interactive behavior between the pre-bored pilot tunnel and the subsequently excavated main tunnels. The information is summarized in Table 2 and the data plotted in Fig.6.

From the results, only 3 cases located to the east of the Chingyin Fault near the eastern portal area showed more obvious interactive effects. In this area, heavily sheared argillaceous rocks of the Kankou Formation were encountered. And the sections of these 3 cases are located in the transition area from the narrower spaced portal to the area with a typical tunnel arrangement. The spacing between the pilot tunnel and the main tube in this area is significantly less than the typical tunnel arrangement. All cases agree with the prediction of interactive behavior according to the criterion proposed with the exception of case 2. Although the criterion would predict slight or no interaction for case 2, the interactive effect may be amplified by the excavation of the two main tunnels. Due to the presence of poor geological conditions and narrow spacing between the tunnels, more obvious interactive effect is expected. Cracking of the segment lining was observed following the excavation of main tubes. This was remedied by strengthening the lining in the pilot tunnel using steel arches and shotcrete.

To the west of the Chingyin Fault, no obvious interactive effect was predicted, which is consistent with field performance observations of the pre-bored pilot tunnel. This is attributed to the better rock conditions encountered and the larger spacing between tunnels adopted.

CONCLUSIONS

A criterion proposed for assessing the interactive effect between tunnels was examined by using the case histories of tunnel construction in the Second Freeway Project. The results showed that the criterion can provide a guide to the planning of tunnel alignment by using the rock properties and in-situ stress levels estimated.

In considering the interaction of Hsuehshan Tunnels, only a short length of the pilot tunnel was affected by the subsequent construction of the main tubes. Over 96% of the tunnel length were considered appropriate. Severe tunnel interaction occurred as the results of the tunnel alignment requirement near the portal and the poor rock conditions encountered. The problem in this tunnel section was remedied by additional support work. This may prove to be a more cost-effective approach than strengthening the lining for the whole pilot tunnel, especially considering the 36 cross adits and 6 large ventilation chambers that need to be excavated.

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